Performance Analysis of Optical Burst Switching Network

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This thesis is submitted in complete fulfillment of the academic requirements
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Declaration

I declare that this thesis is my own work. Where collaboration with other people has taken place, or material generated by other researchers is included, the parties and/or materials are indicated in the acknowledgements or are explicitly stated with references as appropriate.

This work is being submitted for the Master of Science in Electrical Engineering at the University of Cape Town. It has not been submitted to any other university for any other degree or examination.

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Abstract

In this dissertation, after reviewing the new paradigm in the optical switching network invoked by the DWDM technology and studying the changes of the schemes, we design the new optical burst switching networks, analyze the performance of the proposed scheme and interpret the analysis results. For design point of view, the fairness guaranteeing scheme and burst blocking reduction schemes in the mesh networks, loss less burst transmission scheme in DWDM metro ring networks are considered.

As a future broad band optical alternative, optical burst switching has been receive much focus. We review the property of the optical switching technologies such as optical packet switching, optical circuit switching, and optical burst switching. The benefits of the optical burst switching is illustrated. Even though optical burst switching has several advantage, it has intrinsic technology barrier. We study the research activities to remove the basic problem of optical burst switching. Optical deflection, optical burst segmentation, burst cloning, and burst piggy backing scheme is considered.

To improve the network performance, we design optical burst switching network in mesh networks and metro ring networks. We also implement the proposed network by our own developed network test bench.

We verify the proposed network performance by analyzing the network mathematically in terms of blocking rate, delay and throughput. The theoretical results are compared with the simulation results. The verification shows that our proposed schemes outperform those of the conventional scheme. Our mathematical models is also matched to the simulation results.

The interpretation of the verification shows that our assumption and theoretical analysis is well designed. The results illustrate that the difference between the simulation results and mathematical results is within the considerable margin.

The contribution of the thesis is that the performance improvement schemes in both of the mesh network and ring network are proposed and analyzed. By considering feasibility of the future optical networks, proposed scheme in this thesis is more deployable in commercial network in terms of the burst blocking rate and delay as well as the network stability.

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First of all, I deeply appreciate Dr. Alexandru Murgu, who has instructed me during 2 years with valuable advices and academic behavior. I can not deny that his assistance is the basis of my research proposal and this thesis. His valuable comments for my papers make my paper more sophisticate and valuable.

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Glossary

OFMDA (Orthogonal Frequency Division Multiple Access): An popularly used technology for broadband wireless communication by using the orthogonal property of the carriers in frequency domain.

MIMO (Multiple Input and Multiple Output): A technology to be used to increase wireless channel capacity by using channel coding in multi-path environment.

DWDM (Dense Wavelength Division Multiplexing): An optical fiber technology to increase bandwidth by using the wavelength division technology.

O/E/O (Opto-Electro-Optic) conversion: the process of converting optical signal to electrical signal and vice versa.

OCS (Optical Circuit Switching) technology: After setting end to end connection, all of the optical information can be communicated in the optical domain

OPS (Optical Packet Switching) technology: Final goal of optical network technology, all of the optical packet processed packet by packet in the optical core network

OBS (Optical Burst Switching) technology: Interim solution for the OPS, several packets are assembled into the large burst in the ingress node and switched by burst, having a benefit between OPS and OCS

JET (Just Enough Time): offset time based burst classification scheme, the bursts having larger offset time get a high priority compared to that of little one

ECNC (Edge/Core Node Combined) node: network nodes which have an ability to generate burst as well as to transit bursts.

DB (Data Burst): the payload of the burst in optical burst switching

TDB (Transit Data Bursts): bursts generated previous node and transit the current node

OXC (Optical Cross Connector): used for switching optical signal in optical domain

IVF (Immediate Void Filling): burst generation scheme that generate it immediately with void

Chapter 1 Introduction

1 Introduction

1.1 Thesis Proposal and Progress

The initial aims of the thesis are those of improving OBS blocking rate and analyzing TCP performance of the evolved optical burst scheduling scheme. This goals are set to study the OBS performance improvement scheme and to analyse the performance of TCP layer. During several months, there were several trials to achieve these ends.

The final goals of the research are considering OBS scheme to overcome high burst loss rate and performing mathematical analysis on blocking rate or packet loss rate and packet delay in the proposed networks as well as round trip time in TCP layer. In addition, developing strategies of OBS in Optical communication and analysing performance variation of TCP on OBS are expected. Through research activities, we expect the results of throughput in TCP layer regarding end to end packet delay and link utilization and the end to end performance regarding burst loss on TCP and packet loss in burst.

The proposed methodology of the research will be as follows: Firstly, surveying previous works to improve OBS system based on current technology and to proceed further researches, secondly, analysing and verifying proposed scheme by simulation. For simulation, NS-3 is considered one of the open source tools to implement proposed scheme. Due to the high degree of the modification in open source property, change data transmission mechanism in NS-3 and calculating the TCP throughput is considered to be possible to implement OBS module. Finally, comparing the simulation results with theoretically analysed results are predicted.

During activities, to focus to more importance area and get a valuable results in the deployable commercial optical networks, the research topic and simulation tools are changed a little. Regarding the area of performance analysis, focus is changed from TCP layer to the optical transmission layer. This is because TCP performance can be easily achieved by analysing the performance analysis in transmission layer. Secondly, C++ programming language is used instead of NS-3 tools. Because C++ provides more flexibility compared to the NS-3, we can draw a variety of performance analysis results.

1.2 Thesis Overview and Motivations

As the applications consuming high bandwidth have been ubiquitous in modern society due to the advent of wireless mobile technologies, the need of high bandwidth in core networks have been growing in recently. IP-based wireless mobile applications make user to access the Internet regardless of the space and time limitation. This can be possible with the help of the development of the high speed wireless technology such as Orthogonal Frequency Division Multiplex Access (OFDMA) and wireless channel coding scheme such as Multiple Input and Multiple Output (MIMO) in 3G and LET. To satisfy the user requirement, the core network needs to provide sufficient capacity to deal with traffic produced in mobile networks.

The emergence of dense wavelength division multiplexing (DWDM) technology is considered as a solution to meet the tremendously increasing demands of transmission bandwidth driven by the growth of IP-based data traffic[1][2]. At the same time, the necessity to make the next-generation optical Internet architecture is augmented, which can transport IP packets directly over the optical layer without opto-electro-optic (O/E/O) conversions, like optical packet switching (OPS).

Although OPS which can achieve higher utilization is attractive, there are practical technological limitations such as optical buffer and all optical processing. Recently, optical burst switching (OBS) technology has been studied as a solution for optical switching technology in the near future since OBS technology can cut through data messages without O/E/O conversion and guarantee the Class of Service (CoS) without any buffering [3].

Under just enough time (JET) [5], each optical burst is preceded by a BCP that contains information about the burst and the path that is to take through the network. By delaying the burst transmission by offset time, no additional buffering of the data burst is required while the burst control packet is electronically processed at each intermediate nodes in the path. At each node, the burst control packet attempts to reserve network resources to accommodate its correspond burst. If sufficient resources cannot be secured at any node, the data burst would be dropped when burst arrives at that node.

To provide QoS differentiation between high-class bursts and low-class bursts, JET uses different extra offset times for different class of bursts [5]. The basic idea of this scheme is to give a larger extra offset time to a high-class burst, thus enabling a high-class burst to be reserved in advance than a low class burst and giving it a better chance to be preempted. A long offset time enables a high-class burst to be succeeded in making a reservation. Studies have shown that the probability that a low-class burst will block a high-class burst can be negligible when the difference of offset time between these classes is a few times the average data burst length of the low-class [7].

Using a one-way reservation protocol such as JET, the ingress node sends out bursts without having reservation acknowledgements or global coordination. To solve the aforementioned problem, several schemes have been proposed [16, 38]. First of all, to compensate the high blocking probability, deflection routing, burst cloning, resource overprovisioning, and burst segmentation have been considered in mesh networks. Bursts are rerouted to an alternative link when the designated path for the bursts is preempted for another burst in deflection routing scheme [31]. In burst cloning scheme, the bursts are copied and sent twice to the destination [16]. In addition, the packets which are located in the overlapped area in a bursts between contending bursts, are lost only when bursts contend for the same link while the packets in non-overlap area do not drop. This scheme avoids full packet loss in bursts and decreases the packet blocking rate. Resource overprovisioning scheme means that networks are designed to deploy more network resources than needed to reduce burst blocking rate.

In this dissertation, we research the loss performance of an OBS network with completely isolated classes by examining the burst size of low-class bursts, and propose a burst segmentation scheme for low-class bursts to reduce blocking probability and the number of BCP for low-class bursts. Also, to increase the loss performance of low-class, different burst assembly schemes are proposed for each class.

To solve the fairness issue in offset time–based QoS priority scheme, we consider the edge/core node combined (ECNC) OBS network, where all node can generate data burst (DB) with the edge node function and forward DB to the next node with the core node function, and wavelength grouping concept of classifying bursts and assigning them to specific wavelength according to the remaining hops of the bursts. If the node control the sending time of its DB by buffering the DB in the electrical buffer, it will not interrupt the transit data bursts (TDB) generated previous nodes. Therefore, the starting DB can avoid contention by inserting DB among TDB. By doing so, the overall network performance will be improved while this scheme do not affect the loss rate of TDB. We find that the offset-time of TDB affects the throughput of the network.

Even though OBS is considered as a strong candidate of next generation optical transmission scheme, it has some obstacle of high blocking rate and burst assemble delay. To solve aforementioned issues, This dissertation suggests the feasible solutions in Metro Ring networks by using wavelength division multiplexing (WDM) technology to implement collision less transmission. In addition, to resolve poor utilization and synchronization issues in OBS WDM ring networks, this dissertation proposes a look-ahead optical burst transmission (LAOBT) scheme for collision avoidance by inserting generated bursts (GBs) within the void interval which is the size between incoming bursts (IBs). The void size is estimated by delaying IBs at the fiber delay line (FDL) and calculating IBs' residual time to the optical cross connector (OXC). After that, we propose the appropriate scheduling mechanisms for LAOBT to maximize link utilization and mitigate delay increment caused by the FDL.

The Immediate Void Filling (IVF) burst generation scheme, used for burst generation initially, assembles packets to bursts without delay if there is a void between TBs. Because of the immediate burst generation mechanism, the average number of packets in a burst is less than 2 even at a high traffic load. To compensate the property of optical burst switching, we consider the advanced burst assembly scheme while satisfying the delay requirement in optical networks.

1.3 Contribution

In this dissertation, insertion based optical burst transmission schemes, which is a deployable commercial optical networks, are considered. Firstly, we analyze the conservation law and conclude that this law does not use to obtain blocking rate of low class burst, especially in completely isolated classes. Also, we proposed the analysis method for low class burst in this environment and suggest the performance improvement schemes. Secondly, we drive the issues of different offset time and fairness problem in a mesh networks. To solve fairness problem, we suggest the wavelength grouping scheme.

By using this scheme, the fairness problem is solved in mesh networks. Also, with the characteristics of constant offset time, the arriving time of next bursts can be estimated. With this predicted value, the locally generated bursts can be inserted among transit bursts. Thirdly, we design a look ahead collision less burst transmission scheme in a ring networks. Lastly, to sustain the property of burst, we proposed the time-based traffic adaptive burst generation scheme. The analysis and simulation results show that our proposed scheme improve network performance parameters like as delay and throughput.

Our proposed schemes provide implementable network architecture for the future optical network. One of the limitation can be solved by using our scheme and the blocking rate in the mesh network can be reduced to meet the commercial criteria. The insertion based burst generation scheme increase the network throughput.

In the aspect of the novelty, we drive the theoretical analysis model for the delay and throughput in the proposed network. Our proposed analysis is verified by comparing the simulation results. Our analysis methodologies can contribute to future researches in optical burst switching networks.

1.4 Dissertation Outline

This dissertation consists of 6 chapters. In chapter 2, the new paradigm of the optical transmission scheme is introduced and related works are considered as a background of the research. In this chapter, the concept of all optical switching network, optical packet switching and optical burst switching are considered. Besides, the major issues in optical burst switching are thought of such as high blocking rate and fairness in mesh networks. To overcome these drawbacks in OBS, a variety of scheme are considered as a basis of this thesis. In this chapter, the technologies of deflection, burst cloning, burst segmentation and burst piggy backing are dealt with.

In chapter 3, a variety of networks designed to improve network performance are presented. To verify the proposed network, we implement our own simulation test bench by using the computer programming. To improve the fairness issue in offset time based QOS priority scheme, we designed edge core combined networks. By inserting transition burst the network throughput is increased in addition to the achievement of the fairness among same class burst by grouping wavelength in mesh networks. Additionally, we design the loss less DWDM metro ring networks. The loss less burst transmission can be achieve by predicting arriving burst and inserting generated burst in current nodes. This goal can be implemented by using the fiber delay line and the optical splitter. This look ahead optical burst transmission scheme makes optical network more stable.

In chapter 4, we performed the analysis of the proposed scheme in a designed networks environment. The size based burst insertion is considered to improve the network performance.

After mentioning the concept of priority scheme in JET-based OBS networks, the concept of degree of class isolation will be introduced. The effects of the low class burst size in blocking rate are deeply investigated.

The fairness issues is critical in offset time based burst transmission scheme. This fairness violations are normally happened in core network while the number of remaining nodes are different. To remove the fairness violation, the wavelength grouping scheme is considered. The performance analysis results show that there are tremendous performance improvement in proposed scheme.

Besides, the blocking rates and delay are analyzed in a designed mesh networks and metro ring networks, respectively. This analysis is based on the mathematical theory and simulation results. The theoretical results are compared with those of the simulation results. Some of the performance results are considered to be deployable to the commercial optical communication networks. The analysis results show that the proposed scheme is outperformed to the previously proposed schemes.

In chapter 5, we interpret the performance analysis results by investigating simulation and mathematical results. The interpretation analysis shows that the mathematically analyzed results is almost correctly matched that of the simulation results. The delay calculated mathematically in the look ahead optical burst transmission is within the range of the acceptable criteria. The analysis of blocking rate and throughput in mesh network confirms that mathematical analysis is correctly thought of and verified by comparing the simulation results.

Lastly, this thesis conclude by summarizing all of the topics in this thesis in chapter 6, the overall concept of the thesis are summarized and the benefit of the proposed scheme and networks are discussed.

2 New Paradigm and Challenges of the Optical Switching

2.1 A New Paradigm in Optical Networks

Traditionally, circuit switching based wavelength routing scheme has used for optical signal transmission to communication in optical domain. This concept is useful in terms of the secure information transmission. The information can be transmitted without interruption because the connection between source node and destination node are physically connected. This scheme has a disadvantage in terms of the efficiency. The channel capacity would be wasted when there are not information to be transmitted. To improve optical channel throughput, some researchers have considered a new concept of optical switching.

Initially the concept of optical packet switching was considered to increase the transmission throughput. After considering its commercial use, this concept is thought of impractical technology considering current technologies. So researchers have considered another aspect of the technology. Among them, optical burst switching is one of the practical alternatives to be deployable in current technology.

2.1.1 All Optical Switching

In all optical network scheme, all of the signals are manipulated in the optical domain. The optical signal does not need to be converted to electrical signal to process header information. The electrical signal is converted to optical signal at the ingress node and optical signal is converted back to the electrical signal at the egress node. This scheme can increase the transmission speed because all of the signal are handled in optical domain.

The optical domain has expanded to the home by using all optical IP networks, as shown in Fig. 1. The aims of this scheme is that all of the signal process can be only performed in optical domains. In optical domains, it does not need to have the optical electrical conversion and optical electrical conversion. For some developed countries, the concept of Fibre To The Home (FTTH) is implemented after experiencing Fibre To The Curb (FTTC). In addition, at the nearby of the customer's facilities, Ethernet Passive Optical Networks (EPON) has been deployed by using the Optical Line Terminal (OLT) and Optical Network Unit (ONU) at network provider's side and user's side, respectively.

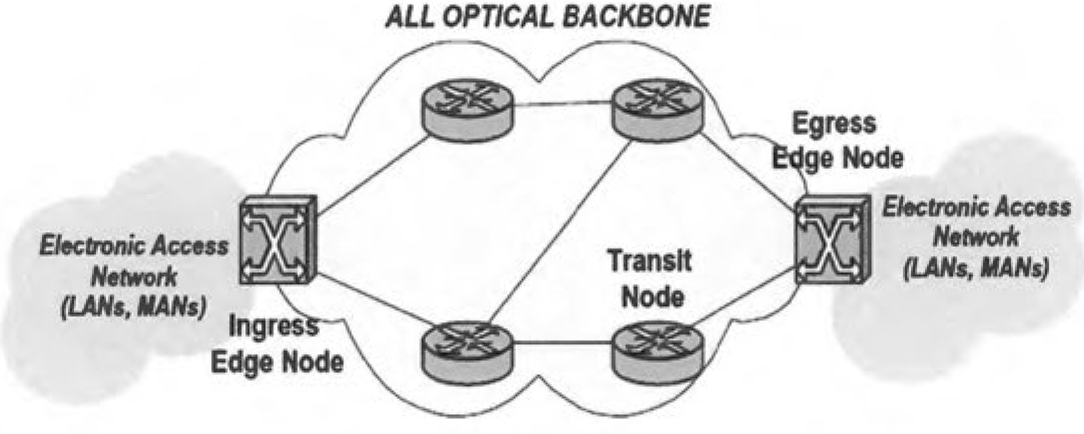


Figure 1. All optical IP networks [11].

In the environment of all optical network, electrical signals are converted to the optical signal. After converting to the optical signal, all of the signals are dealt with in the optical domain. The signal processing can be performed efficiently. At the egress node, the optical signal need to be converted back to the electrical signal. The premise of the all optical network is that optical process, optical memory, and optical buffers are developed to process all optical signal.

2.1.2 Optical Packet Switching

To solve lower throughput issues in optical circuit switching technology, researchers have thought of the optical packet switching as an ideal optical switching scheme because of its high bandwidth efficiency of this scheme. In optical packet switching, similar to its counterpart of packet switching in electrical domain, the link only is occupied when the optical signal exists on the link. Every optical packet is processed individually. The header information of the optical packets is decoded at the core nodes and the next node are selected considering routing information.

After deciding next node, the packets are transmitted to the next node. During this time, the optical packet needs to be delayed in optical domain. Optical packet switching has barriers in regard to current optical technology [11] because there are some issues to overcome considering current technologies. Some researchers have tried to solve the problems the limitation of optical buffer and all optical processing.

The two premises of the implementation of optical packet switching is the optical signal processing and the optical buffer. All of the header information is handled with optical signal processor. During decoding and deciding routing information of the packet, the payloads need to be delayed by in the optical domain. However, it is difficult to delay optical signals in the current optical technologies. All of these technologies has limitation to be deployed with in several decade even though there are technologies such as fiber delay line to delay optical signal. These are reasons why optical packet switching is only considered as the future optical switching technology [2, 11]. A lot of schemes to avoid the bottleneck in forwarding engine in optical router are being studied, utilizing optical packet or burst techniques by using the electronic buffering to implement IP over WDM. However, the scheme tried to avoid contention directly in the optical domain is only considered in WDM optical packet switching.

To removing the bulk of the switching burden into the optical domain is the one of the goal of this researches, permitting compatible scaling of the switching capability with WDM transmission capacity. This improvement scheme has assumed a hybrid solution, achieving decoupling between the throughput and the routing/forwarding processes.Transmission and switching are performed in the optical domain, while routing and forwarding are carried out electronically, where the relatively complex packet header processing happened independent of the optical payload. This decoupling effectively allows the optical packet layer to support a variety of networking protocols while utilizing the power of WDM transmission.

While the optical header processed for decoding signaling such as routing information, the optical payload should wait. The implementation of the optical buffering is the use of the fiber delay line considering current technologies. Several kilometers of the fiber lines are necessary to delay several micro second. To reduce the fiber, the high speed processors are needed in the core routers. Due to the high speed header processing, the router need lots of power. The power efficiency need to be considered. The synchronization between optical header and the payload is critical. Exact length of optical fiber is needed to meet the criteria.

Due to the nature of optical buffering such as fiber delay line, the payload duration is variable, whatever its content; the network throughput is changed according to payload bit rate which may vary from 10 Gb/s and up, with easy upgrade capability. Besides, the wavelength dimension is important for transmission capacity as well as in performing practical contention resolution to improve network performance.

2.1.3 Optical Burst Switching

The optical burst switching has been considered as the temporary solution of optical packet switching. It partially has the property of optical circuit switching and optical packet switching. The basic concept of optical burst switching is that, before transmitting the optical bursts which contain lots of packet assembled at the ingress node, the burst control packet (BCP) is transmitted in advance to make a reservation for the burst. Data burst can be cut through the link BCP already assigned without electoral signal conversion. For the control packet, BCP, it has to be converted to the electrical domain to decoding routing information. During header processing, the optical signal should be delayed. For this reason the BCPs are transmitted in advance. The time gap between data burst and the BSP is called offset time. The offset times become smaller when the information proceed to the destination node due to the header processing time in the core node. The basic wavelength assignment and signaling operation of the BCP and data burst are briefly illustrated in figure 2.

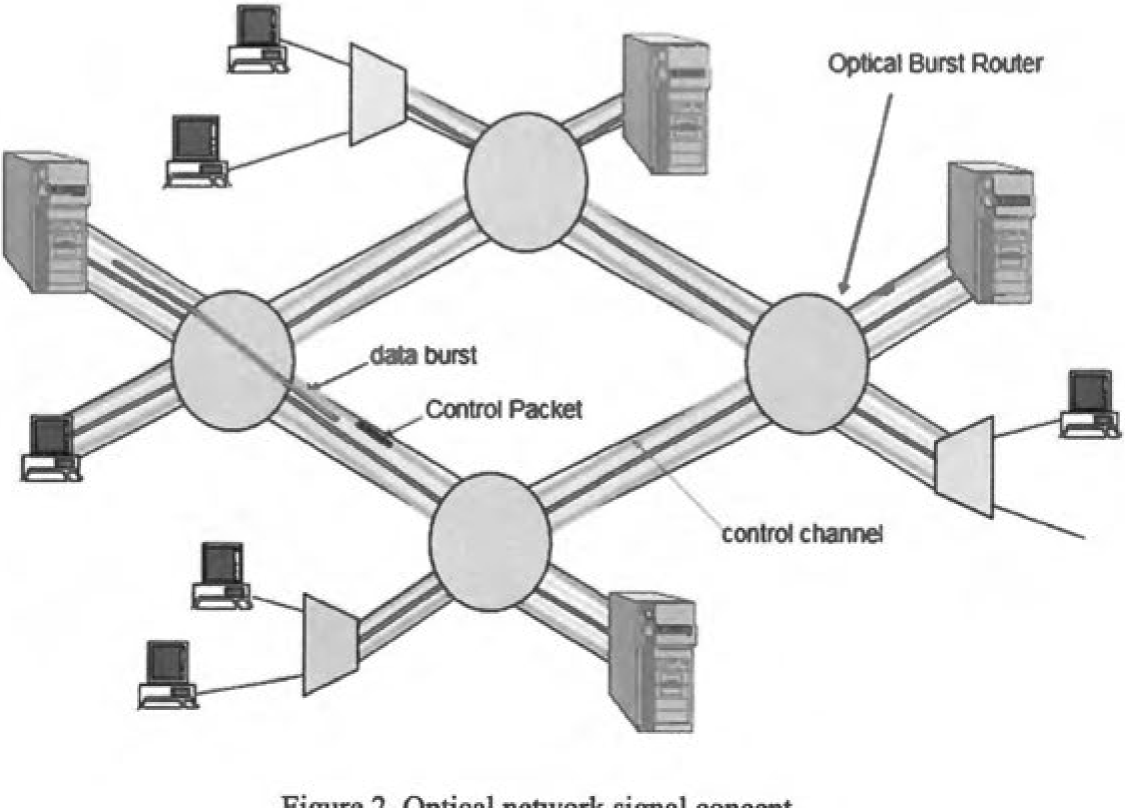


Figure 2. Optical network signal concept.

By doing this the link utilization and delay can be improved compared to those of optical circuit switching [5, 11]. There are two kinds of OBS control schemes: Just-In- Time (JIT) and Just-Enough-Time (JET). In JIT, after the end to end link connection setup is done for the burst by BCP in requesting network resources for every link and Ack signal is received from the egress node, the data bursts can be transmitted through the reserved link [8, 9].

This acknowledge-based optical switching scheme has the advantage of contention free transmission while there are longer delays because of the link connection setup time before transmission. To reduce the connection setup time, JET is considered [3]. Without end to end link reservation, the BCP is sent to the destination node before transmitting data bursts.

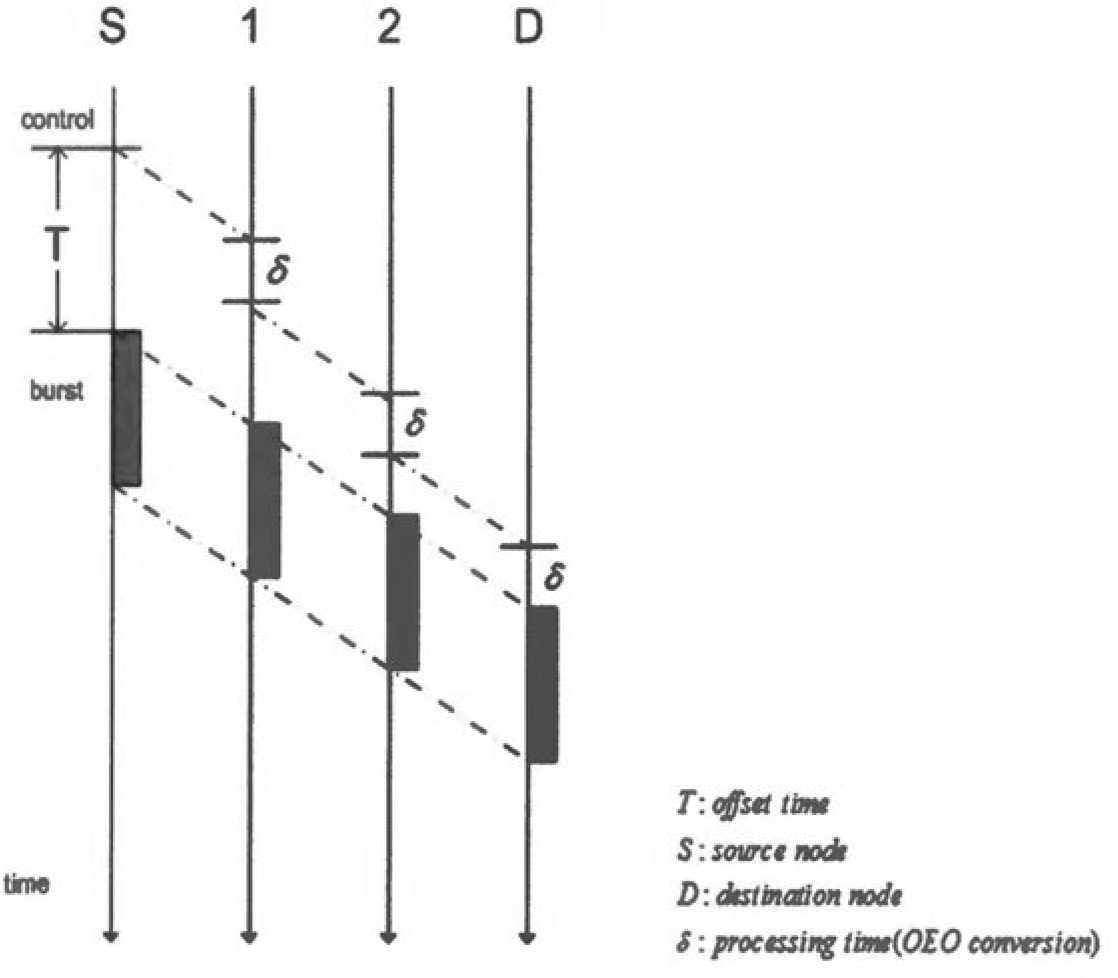
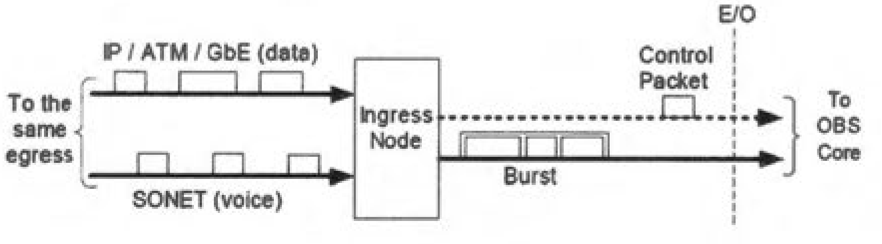


Figure 3. Offset time change during burst propagation.

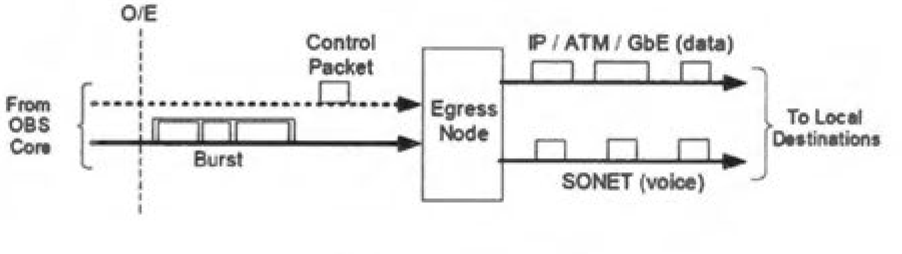
When control packet arrives at intermediate nodes, the routing information is decoded by converting the optical signal to electrical signal. After being used to decide the next node in electrical domain, the BCP is converted to optical signal again.

Due to the time spent at core nodes for header processing, the offset time will decrease while the BCP and data bursts pass along core nodes as shown in figure 3. Similar to the JIT, the data burst in JET can be cut through the network. However, due to the ackless property, it has the possibility of being dropped when BCP does reserve link because of lack of network resource. When the data bursts arrive at egress node, the bursts are disassembled into the packets.

OBS management relies on the information of control channel being manipulated in the electrical domain while payloads use data channel and are transmitted without conversion to electrical domain. To differentiate the quality of service (QoS) between bursts, offset time is commonly used in JET. Bursts which have a longer offset time, have higher chance to preempt the link compared to that of shorter one [5]. When the burst proceed the networks the offset time goes to be decreased. If the offset time is not enough, the early arrival occurs and it make bursts dropped because of the resource reservation failure.



(a) Burst Assembly



(b) Burst Disassembly

Figure 4. Burst assembly/disassembly at the edge node [51].

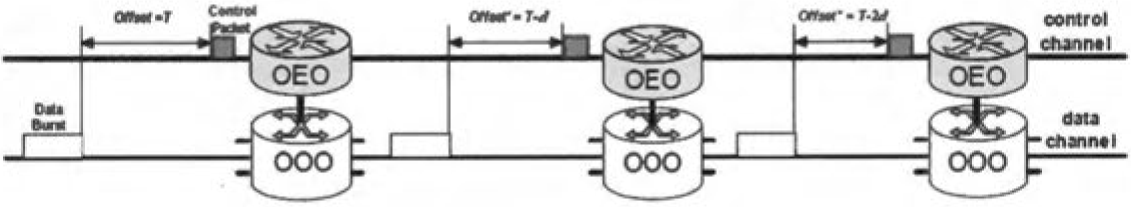


Figure 5. Separated transmission of data and control signal [51].

Under JET, each optical burst is preceded by a BCP that contains information about the burst and routing after assembling packets at the ingress nodes as shown in Fig. 4. By delaying the data burst transmission by offset time after transmitting BCP, no additional buffering of the data burst is required while the burst control packet is electronically processed in each intermediate node in the path as shown in Fig. 5. At each node, the burst control packet attempts to reserve network resources to accommodate its burst in Fig. 5. If sufficient resources cannot be secured at any node, the data burst is dropped when it arrives at that node.

2.2 Current Issues and Challenges in OBS

2.2.1 Challenges of the OBS

OBS has intrinsic limitations to be deployed in the commercial networks transporting high speed and high volume data. OBS has inevitable high burst contention rate due to its one-way (Ack-less) transmission mechanism [1]. High burst blocking rate needs to be controlled. This stems from the Ack-less property of one-way resource reservation. In other words, if the control packet fails to reserve the channel because of the lack of network resource, the data bursts would be dropped [4].

In JET, the bursts have an equal QoS if they have the same offset time. However, the offset time is normally reduced gradually when data bursts pass through core nodes. Therefore, the offset time is different between the bursts. This causes the fairness violation, even though they initially have the same offset time at ingress node, because the offset times between the same class bursts are not equal at the intermediate nodes [18]. Another major issue is the early arrival [23]. When the data bursts arrive earlier than the BCP, the data bursts tend to be dropped because the data burst arrives before the BCP reserves the channel.

The loss of the bursts has a critical effect on TCP/IP networks. All of the TCP sessions in a bursts are to go to the slow start stage at the same time even though one burst is dropped. This synchronized dynamics of window size change in TCP layer would make the whole network traffic fluctuating. So without solving this data transport reliability problem in OBS, the CDN capability will remain limited by network layer controls. This kind of network influence is only considered in optical burst networks because optical burst contains lots of TCP session. To reduce the effect of synchronization, the concept of TCP session dispersion is considered.

2.2.2 Performance Enhance Schemes

To improve the performance of OBS, several mechanisms have been derived. First of all, to compensate the high blocking probability, deflection routing, burst cloning, resource overprovisioning, and burst segmentation have been considered in mesh networks.

2.2.2.1 Deflection Routing

Basic idea of burst deflection is that unused links can be utilized rather than dropping burst when congestion happens. As shown in Fig 6, when reserved link is not available, alternative link can be used for burst routing. This scheme improves the blocking rate while increasing complexity and traffic volume. To implement deflection routing, the optical routers need to have the routing table to deflect bursts when primary links are congested. This may increase the complexity of the networks.

Figure 7. shows the another example of the deflection routing. In this example, bursts are rerouted to an alternative link when the designated path for the bursts is preempted for another burst in deflection routing scheme [23].

When the burstl and burst2 are arriving at the same time at node D and these bursts want to be routed to the node F via link D-F, one of the bursts should be dropped. There are two options to prevent the burst dropping. One of them is to use wavelength converter. One of the burst can be converted to another wavelength. This can be possible when there are available wavelength and the core nodes have the capacity of wavelength conversion.

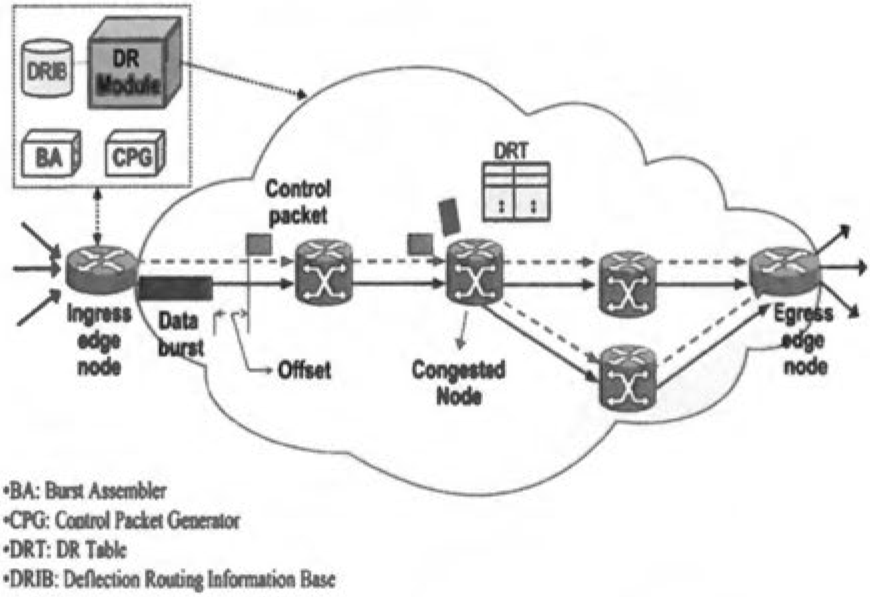


Figure 6. OBS network with deflection routing [15].

The other solution is to deflect the burst to another available link. In this example, one of the burst can be detoured to the link D-E-F to reach the node F. By doing this some of the burst can be avoided the blocking. However, this deflection routing can induce extra traffic volume and is likely to degrade the overall network performance.

There are several scheme for deflection routing in terms of the use of buffer. Deflection routing may be implemented with or without output buffers [23]. With bufferless deflection routing, the additional offset time need to be added with the base offset time at the source node. Also, deflection attempt must be restricted to avoid the early arrival problem. The control packet contains the number of deflections information and if this deflection number is exceeded the threshold value, the deflection route does not work properly.

Allocating proper value of offset time delay is important critically because insufficient delay induce the early arrival problem and larger delays will make burst delayed in longer time. At a light traffic loads, bursts do not need to deflected and hence smaller offset delays are enough. Longer offset times are useful if the traffic in the network is medium volume. Appropriate offset time may be adaptively assigned in terms of the traffic load of the network [37]. To implement dynamic delay, blocking probability need to be calculated at regular intervals based on the negative acknowledgements received at the source node. Based on this information, offset time may be determined using reinforcement learning. However, the delay increases and in the worst case it can be 52 times higher than the normal offset time requirements [36].

Adaptive offset time in traffic load provides significant performance increase over compared with previous deflection routing [35]. With the increase in the number of times a burst is deflected the required offset time delay increases rapidly. In general, the initial offset delay is large enough for handing multiple deflections. However, the entire delay may not be used often. Wavelength reservation approach is used to decrease the probability of deflection numbers [37]. In this scheme a particular number of wavelengths are exclusively assigned at every node for alternative path. The wavelength reservation scheme have a performance improvement compared to the limited buffers deflection scheme [38] as far as overall blocking probability is considered.

With high traffic load beyond some limit, the performance of deflection routing degrades rapidly [34]. This is due to more number of deflections required and thus generates extra high load. Hence, the deflection needs to be limited during heavy load condition to prevent degradation of network performance. The use of FDLs or local traffic based access control was suggested for stable OBS network [31].

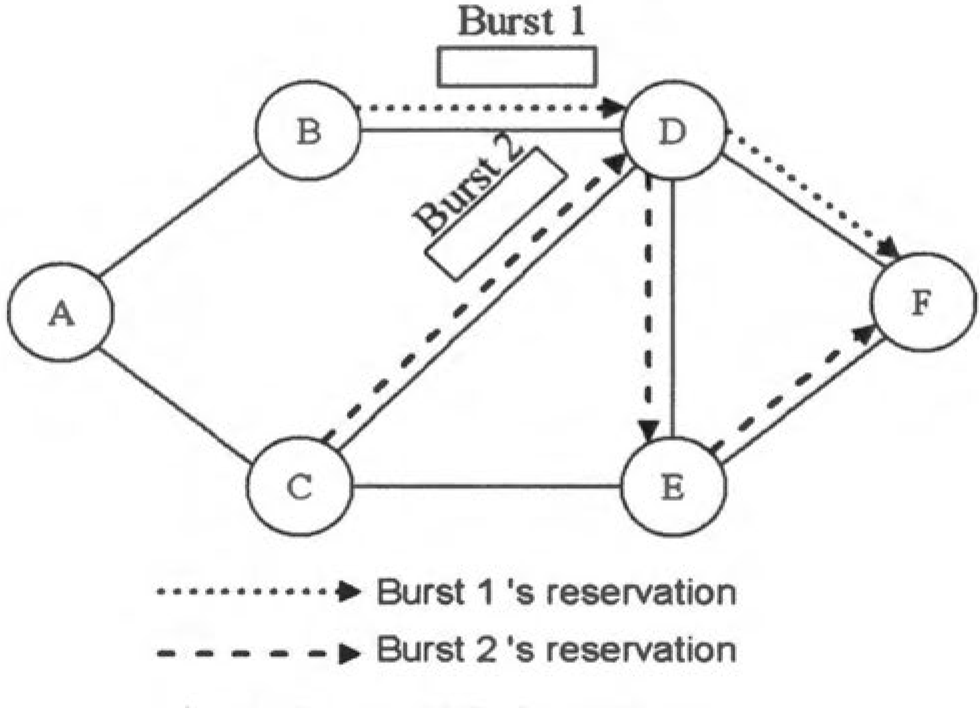


Figure 7. Concept of deflection routing [23].

There are different approaches presented for limiting the number of deflection attempts. In [33], deflection of burst is done with set value of probability during contention. The deflection probability value is adjusted or updated based on change in traffic load. In [36] restricting the deflection attempt is achieved by exclusively allocating the number of wavelengths on paths for primary bursts. This approach reduces degradation and improves the throughput at very high loads. In preemptive priority scheme, a first-choice burst is given the right to preempt a reservation that has been scheduled for a deflected burst [38]. This scheme provides better protection against poor performance at overloads.

2.2.2.2 Burst Synchronization: Slotted Burst Transmission

Burst synchronization scheme, which idea is borrowed from the slotted Aloha protocol, is also considered. By initiating bursts transmission synchronously, the overall blocking rate could be almost reduced by half theoretically. One of the examples of the burst synchronization is shown in figure. 8 [17]. In this example, the bursts in the networks try to transmission at the same time in every nodes as well as in the same node among the same wavelength.

Some research results shows that the burst synchronization schemes have a benefit compared to that of normal burst transmission scheme. One of the premise of successful deployment for slotted burst transmission is that whole optical burst network need to use same clock and all of the nodes should know the delay information among the links. When considering high speed optical network speed, adjusting timing information need high technology.

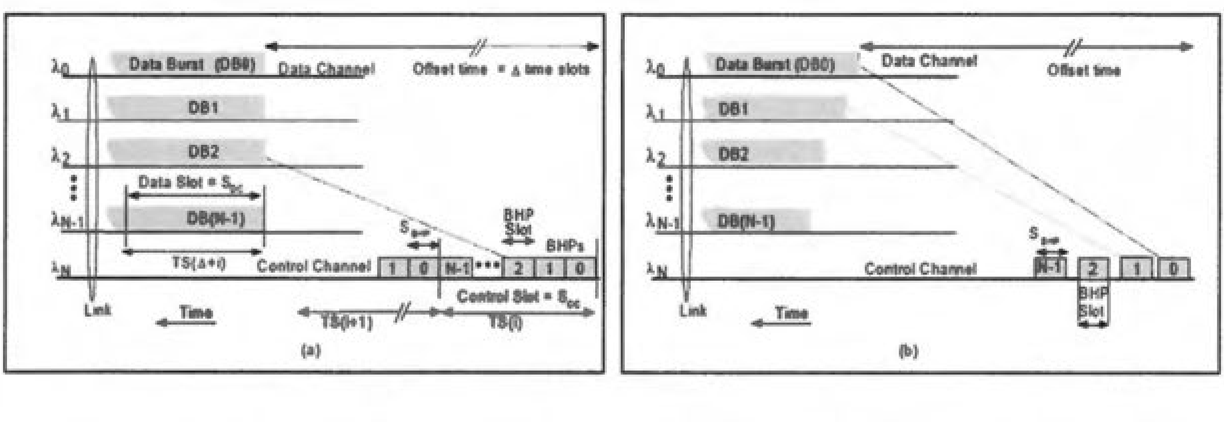


Figure 8. (a) Synchronous slotted (b) Asynchronous unslotted transmission [52].

2.2.2.3 Burst Cloning

In burst cloning scheme, the bursts are copied and sent twice to the destination [16]. The details of burst cloning is described. The original copy of a burst is termed as the original burst, and the duplicated copy of a burst is termed as the cloned burst. The traffic consisting of original bursts and cloned bursts is referred to as original traffic and cloned traffic, respectively. The node at which the cloning is done is referred to as the cloning node. In burst cloning, there are several aspects to be considered. First of all, the number of cloned bursts for each original burst need to be considered. Secondly, the selection of the cloning node is thought of. Lastly, the routing for the original burst and the cloned burst should to be considered.

In burst cloning, one or more cloned bursts can be made for each original burst. On the other hand, if more copies are made for a burst, the possibility of data loss for the burst is lower. In other aspect, if more copies are made, then more cloned traffic is added to the network. Cloned bursts may contend for network resources with original bursts, which may result in increasing loss for original bursts, which in turn may increase data loss instead of reducing it.

To prevent cloned traffic from interfering with original traffic, a traffic isolation mechanism by using priority-based preemptive burst scheduling is considered. Original bursts are assigned high priority while cloned bursts are assigned low priority. When scheduling bursts, the high priority burst will always be scheduled if there is a contention between a high priority burst and a low priority burst, even if the low priority burst has already been scheduled. From the high priority traffic's point of view, there is no low priority traffic present in the network. The traffic isolation guarantees that the performance is at least as good with burst cloning as without cloning.

Another vital problem in burst cloning is the selection of the cloning node for a burst. In principle, the cloning node for each source destination pair could be different. A tightly related problem is the routing of the original burst and the cloned burst. The general path structure for burst cloning is shown in figure 9.

An original burst is first sent along the common path. After the cloned copy is made at the cloning node, the original burst will then continue along the primary path while the cloned burst will be routed through the cloning path. The common path would be null if the cloning node is the source node. The primary path and cloning path would be null if there is no cloning for the burst. (We can also view this situation as the case in which the cloning node is the destination).

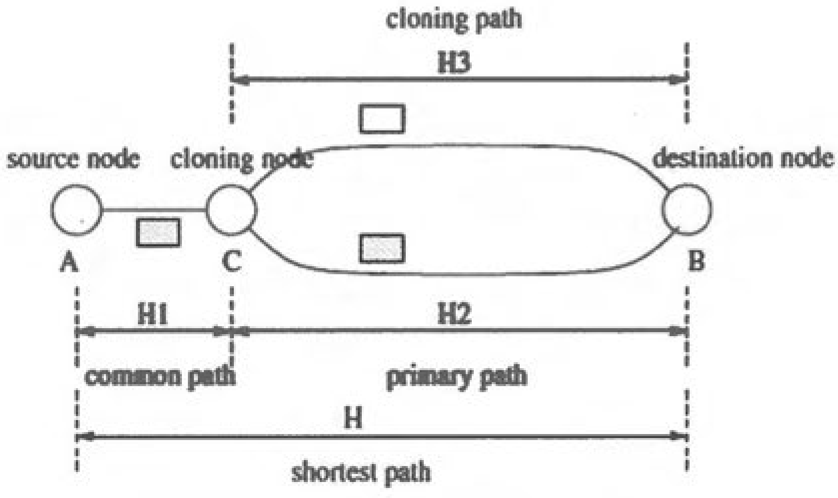


Figure 9. Burst cloning scheme [16].

Since a cloned burst is a backup in case the original burst is lost, it is reasonable to keep the loss of original bursts as low as possible. Hence, we choose the common path and the primary path to be on the shortest path from the source to the destination.

After choosing the primary path, we must make a decision on whether the cloning path should be link-disjoint or even node-disjoint from the primary path. In this paper we are aiming to minimize data loss, and are not considering the protection issues. Therefore, the cloning path is allowed to be partially overlapped with the primary path, except on the first hop of both paths.

The scheduling of original bursts, due to the traffic isolation mechanism, is independent of the selection of the cloning nodes. Hence, we focus on the cloned bursts. On one hand, if the original burst is lost on the common path, the burst cannot be cloned. Thus, the common path should be shorter.

2.2.2.4 Burst Segmentation

To reduce blocking rate in a burst, burst segmentation has considered. The packets which are located in the overlapped area in a bursts between contending bursts, are lost only when bursts contend for the same link while the packets in non-overlap area do not drop. This scheme avoids full packet loss in bursts and decreases the packet blocking rate [11]. Resource overprovisioning scheme means that networks are designed to deploy more network resources than needed to reduce burst blocking rate. The details of this scheme will be investigated in detail in the following chapters with analysis and simulation.

2.2.2.5 Burst Contention Resolution Scheme

By implementing optical buffers such as FDL and buffering burst, some bursts could avoid burst blocking [53]. This scheme needs sophisticated time management as well as having long fibre line. When two bursts contend to reserve the same link at the same time, one of the bursts is delayed by feed backing in the delay line.

The length of FDL determines the time for delaying bursts. To provide several types of delay, the lengths of fiber are differentiated according to the overlapping contention duration. In this example the node should have exchange bursts by using the electrically controlled optical switch in the core nodes.

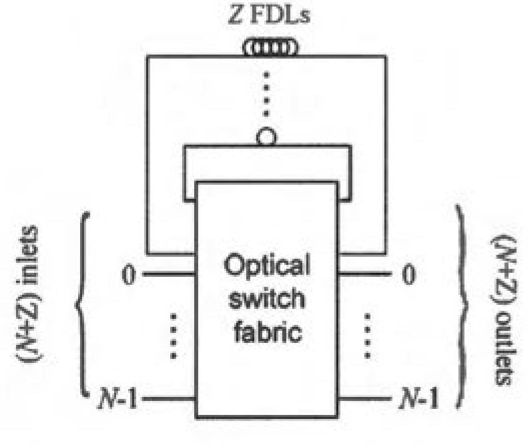


Figure 10. OBS Switch with Different FDL Arrangement [53]

2.2.2.6 Burst Piggy Backing

The error dispersion scheme in optical burst switching is to be considered. One of the popularly used scheme for error dispersion is the interleaving. In figure 11, the details of the interleaving scheme is illustrated. In the wireless communications, the bit errors are likely to be occurred in the bursty manner. Due to the multipath fading in the wireless channel, a lot of bits are vulnerable to the information loss. For instance, if the big objects such as bus, airplane, and train pass across the line of sight, several bits will be lost because of large delay spread of the receiving signal. This burst loss of the information can not be recovered by using the error correction schemes such as cyclic redundancy code (CRC) and Viterbi decoder. This bit dispersion scheme can be applied to reduce burst error in optical burst switching network to prevent TCP synchronization, which cause the critical effect in terms of the network stability.

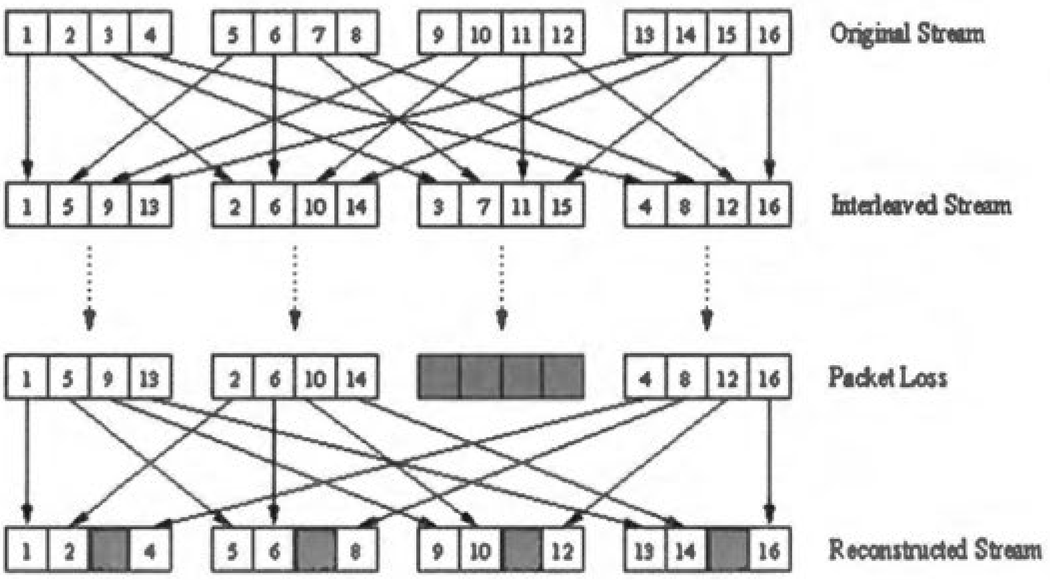


Figure 11. Interleaving scheme: error dispersion method [23]

To prevent the burst error, interleaving method has used in multipath wireless environment. In this scheme, the original bits are dispersed by scrambling them. By doing this, the original bit streams will be randomly distributed among different data frame. When the burst errors occurs, the dispersed error can be recovered by using the channel coding scheme such as convolution and Viterbi decoder. The error recovery ability depends on the length of channel coding and the number of convolution encoder at the transmitter.

The OBS also has characteristic in terms of the burstness of the loss. This is because there are a lot of packets in a burst. When a one burst is blocked in the network, whole packets in the burst will be dropped. This large packet loss has a critical effect on the TCP layer because the size of the window length will be drop synchronously. This synchronization make network unstable and deteriorate the network performance.

To prevent this network disaster, the piggy backing concept is considered. It is different from burst cloning scheme which copy all of the burst. In piggy backing scheme, small portion of the burst is piggy backed in the following burst as shown in figure 12. When the original burst collides, the portion of information piggy backed in another burst can be recovered successfully. In this figure, the portion of the burst No.3 can be recovered from piggy backed information in burst No. 4 when all of the burst is dropped.

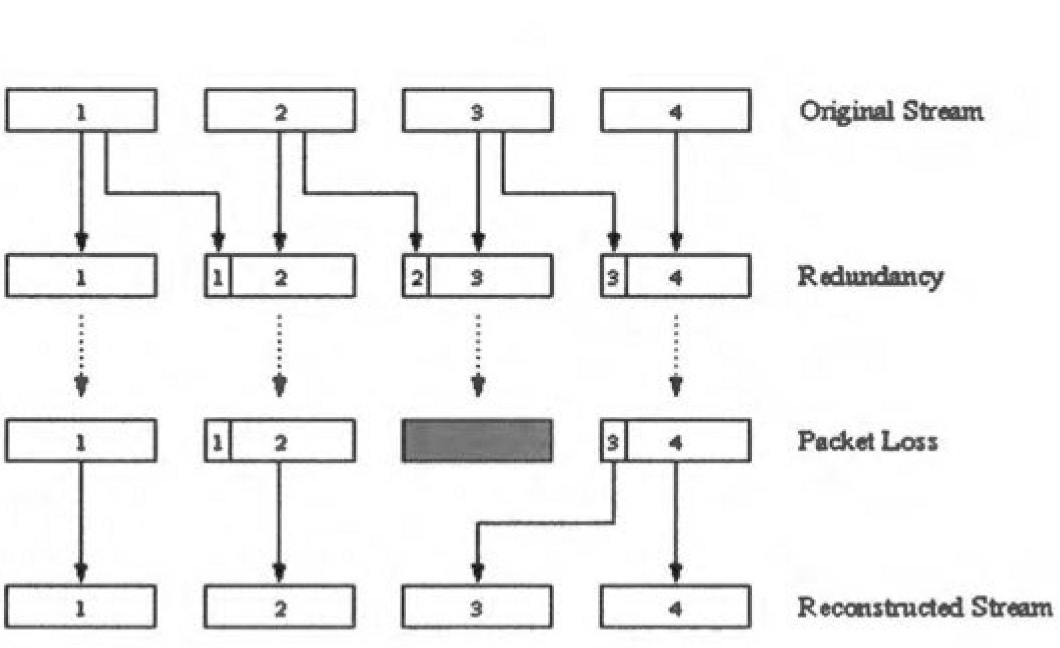


Figure 12. General piggybacking scheme [24].

2.2.3 Issues on commercialization in OBS

There are several limitation to be commercialized in network environment when considering current optical technologies. First of all, due to the lack of the optical buffer, both of OPS and OBS have difficulties to prevent high blocking rate. It is the causes of the low network performance. This is the reason why OBS still remains in research domains. High blocking rate affects the end to end network performances such as throughput and delay. To enhance the QoS and QoE, the aforementioned barriers need to be solved.

However, the commercialization of OBS is possible considering overprovisioning network. By utilizing more wavelengths needed, the blocking rate will be decreased to the point which is acceptable in the commercial networks. The rate of the increase of wavelength in OBS network would be little compared to that of OCS. By designing optical network sophisticatedly, in the author's viewpoint, the commercialization is possible.

2.3 Concluding Remarks

In this chapter, we introduced the new concept in the optical switching research area. Due to the property of the hybrid circuit and packet switching, optical burst switching technology has received lot of attention. However, while it has lots of benefits, there are some limit to overcome to be deployed in commercial networks. With property of ackless resource reservation scheme, OBS is vulnerable to the blocking rate. Fairness among the same class burst is another issue to be address. This fairness violation happen when the number of remaining destination is different among burst in offset time based QoS priority scheme. Early arrival is the other issue to be solved. If the data burst arrived before the control packet, the data burst would be dropped because the node do not ready to deal with because it does not have any information regarding routing.

To address these problem, several schemes have been considered among researchers. First of all, to compensate the high blocking probability, deflection routing, burst cloning, resource overprovisioning, and burst segmentation have been considered in mesh networks. Bursts are rerouted to an alternative link when the designated path for the bursts is preempted for another burst in deflection routing scheme [31]. By doing this, the overall blocking rate can be reduced while the traffic volume increase to some extent. In burst cloning scheme, the bursts are copied and sent twice to the destination [16]. The traffic volume increase while blocking rate decrease in this scheme. In addition, the packets which are located in the overlapped area in a bursts between contending bursts, are lost only when bursts contend for the same link while the packets in non-overlap area do not drop. This scheme avoids full packet loss in bursts and decreases the packet blocking rate. This scheme needs to synchronize timing of the bursts. Resource overprovisioning scheme means that networks are designed to deploy more network resources than needed to reduce burst blocking rate. Burst synchronization scheme is also considered. This concept is borrowed from synchronous Aloha protocol. By generating bursts simultaneously, the blocking rate would be decrease compared to the non-synchronization protocol. In the following chapter, we design the optical burst switching network in the mesh networks and metro ring networks. The purpose of the design of mesh network is that of reducing the blocking rate while that of metro ring network is to reduce delay. The aims of both of the networks are to increase the network throughput.

3 Design OBS Networks and Implementation

3.1 Fairness Guaranteeing Mesh Networks

3.1.1 Edge Core Node Combined Network

In this section, we consider the edge/core node combined (ECNC) OBS network, where all node can generate data burst (DB) with the edge node function and forward DB to the next node with the core node function. If the node control the sending time of its DB by buffering the DB in the electrical buffer, it will not interrupt the transit data bursts (TDB) generated previous nodes.

Therefore, the locally generated DB can avoid contention by inserting DBs among TDBs. By doing so, the overall network performance will be improved while this scheme do not affect the loss rate of TDB. We also find that the offset-time of TDB affects the throughput of the network.

In Figure. 13, the typical network model in the conventional JET OBS network is shown. In this model, the ingress node 1, 2, and 3 send data bursts to the egress node 5 through the core node 4, respectively. Data bursts from the three ingress nodes should contend for the same resource at the output port of the core node 4. If we assume that data bursts are arriving at a bottleneck node with Poisson distribution and the number of channel is k and traffic loads for node 1, 2 and 3 are ρ_1, ρ_2, and ρ_3, respectively, then the burst blocking probability with no buffer can be calculated by using the well-known Erlang loss formula $PB\ (k;\ \rho_1,\ \rho_2,\ \rho_3)$. But, in the mesh-type networks, the blocking rate will be changed because of the edge/core node combined functions.

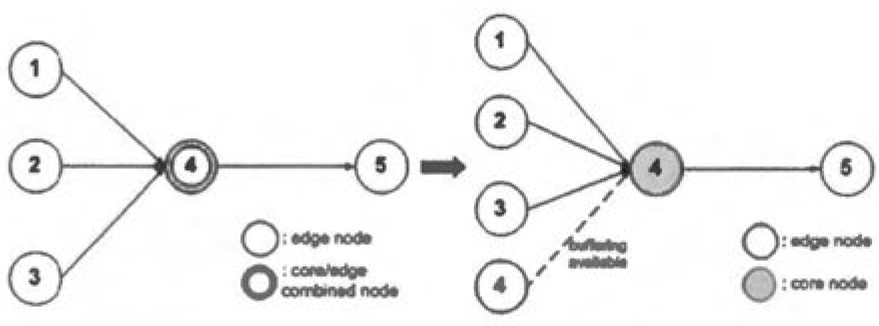


Figure 13. Network model in the conventional OBS networks.

We investigate the performance of the ECNC OBS network as depicted in figure. 35, In Figure. 35 (a), the edge/core node combined, the node 4, performs the egress function as well as the core function. Thus, it both generates new bursts as an ingress node and cut-through bursts from ingress nodes as the core node. Depicted as the logical model in Fig. 18 (b), data bursts from 4 also contend for the outgoing port. Thus, burst blocking probability can be calculated by *PB* (k; ρ_1, ρ_2, ρ_3, ρ_4). It is noted that the node 4 do not have buffers. Instead, self-generated data bursts are immediately sent to the outgoing port and contend with TDB after assembled by using the conventional burst assembly schemes [1, 2].

We know that node 4 has the capability to buffer self-generated data bursts for the purpose of void filling between TDB. We propose a new scheduling algorithm for ECNC OBS network to improve throughput as well as reducing the data burst loss rate. In figure. 15, data bursts from 3 ingress nodes contend for the outgoing port of the node 4, however data bursts generated from the node 4 do not contend with TDB but fill void intervals. This void-filling is based on the two capabilities of the node 4, one is the monitoring capability for all voids in the data channel scheduling table and the other is buffering capability to shift data bursts generated by node 4. Thus, the burst blocking probability for all inputs (ρ_1, ρ_2 and ρ_3) can be calculated by *PB* (k; ρ_1, ρ_2, ρ_3) where ρ_4 has no impact on the loss probability. Compared to loss probability with conventional schemes, *PB* (k; ρ_1, ρ_2, ρ_3, ρ_4), the proposed scheduling scheme achieves drastic loss rate reduction for data bursts.

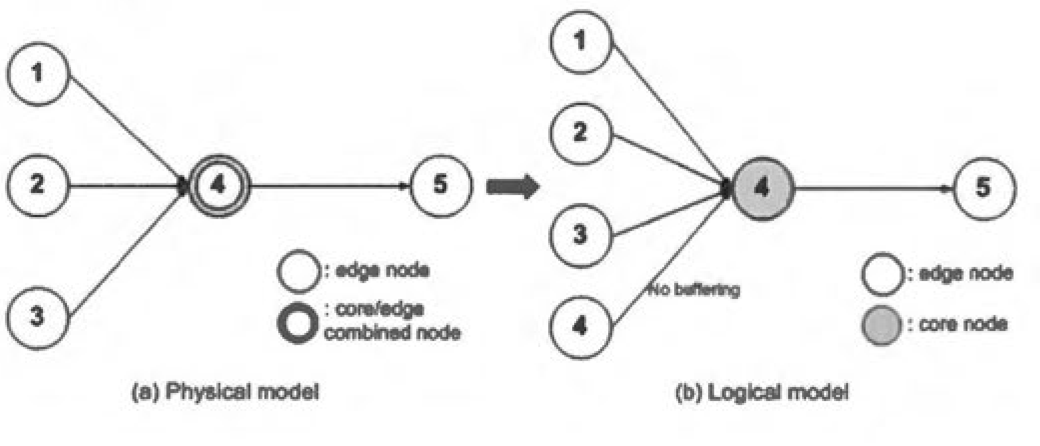


Figure 14. Network model in the ECNC OBS networks.

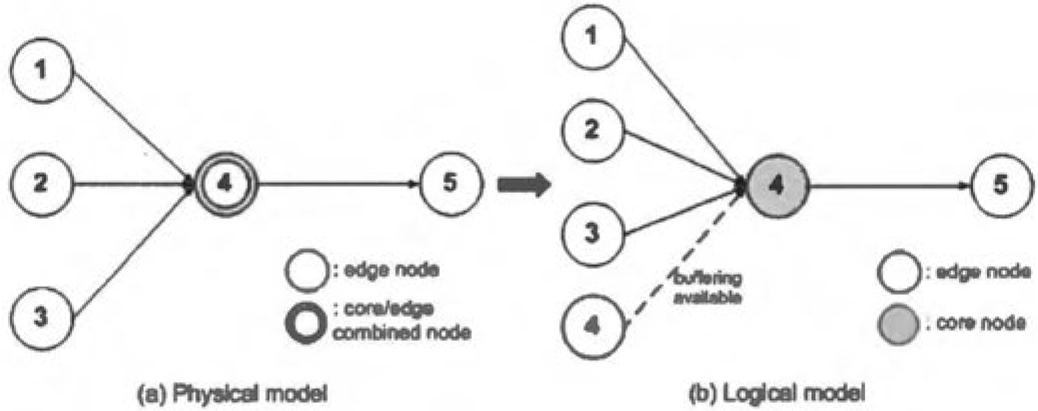


Figure 15. Network model for the new data scheduling algorithm ECNC.

The mesh network is popular topology as a backbone networks. As an example of mesh network, the topology of NSFNET is shown in figure. 16. In mesh type network topology, every node has the ability of being edge and core nodes. To transmit data from source to destination node in OBS networks, source node assemble packet to make burst [3, 6]. Following the BCP, DB follows BCP after offset time. The offset time is determined by the number of hop between source and destination and QoS of the bursts. Therefore, the value of offset time is not the same in OBS nodes even through the DB have the same class of service.

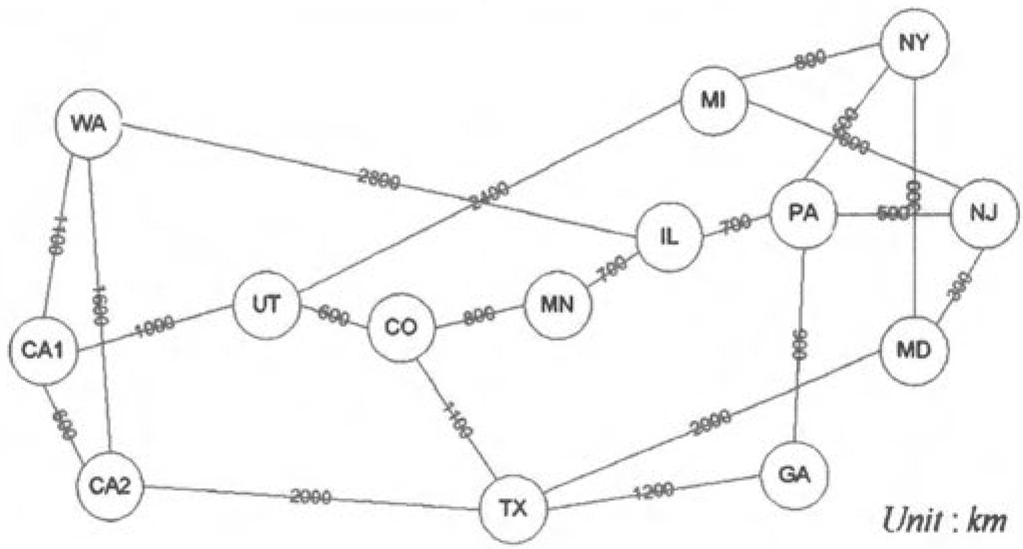
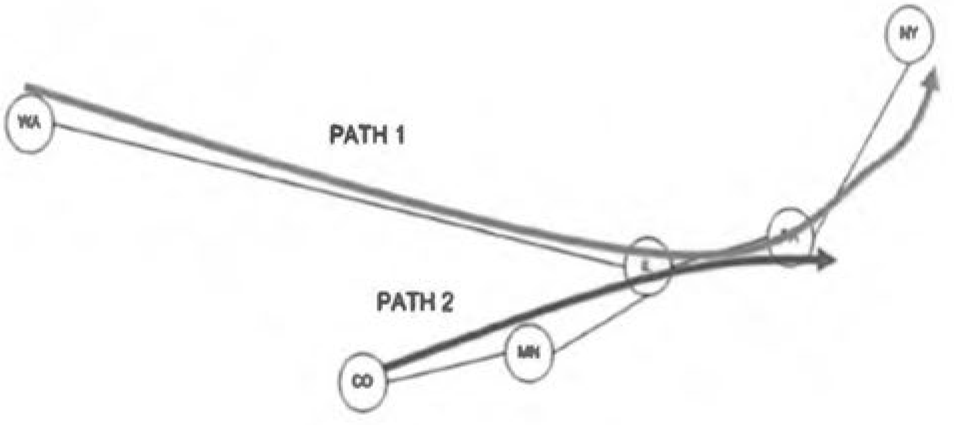
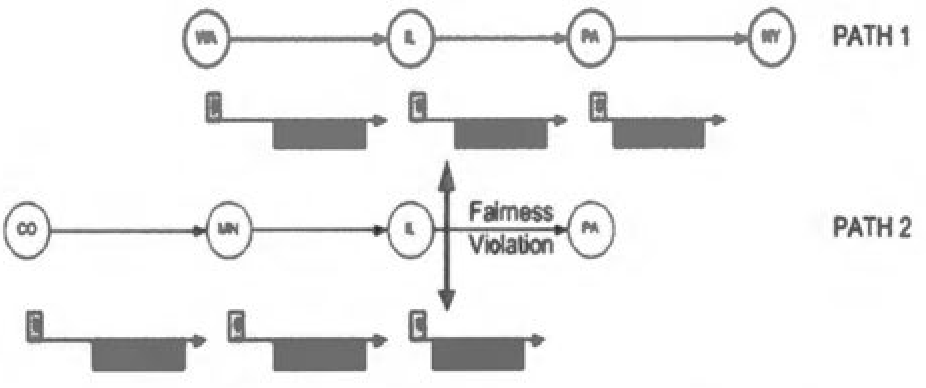


Figure 16. NSF network topology.



(a) Share same link.



(b) Fairness violation at link between IL and PA.

Figure 17. Fairness Violation in Mesh Networks.

As mentioned, the QoS of bursts in OBS network is determined by offset time of the bursts [9]. But the offset time in mesh network is different due to the different number of remaining hops at intermediate nodes as shown in figure. 17. In Figure. 17, the offset time of path 1 is greater than path2 because the remaining number of hops for path1 is two than for path2 is one. Therefore, the bursts in path1 have more priority than in paht2 at node IL. As we explained in this example, the fairness problems will be invoked among the bursts which have different routing path even though they have the same priority.

3.1.2 Fairness Guaranteeing Network Node

To provide fairness among bursts and transmit data more efficiently in mesh net-work, we design OBS node as shown in figure. 18. In this structure, locally generated bursts are separated to the one-hopping (OHG) burst and several-hop-going (SHG) bursts. The SHG bursts are transmitted to the next hop by using the exclusive wave-length group. By doing so, SHG bursts do not affect the performance of TDB. In case of OHG bursts, due to the ability of knowing the void interval among transit bursts, OHG bursts can be inserted between TDB as explained later.

For the one-hop passed (OHP) bursts, which traveled only one-hop within exclusive wavelengths with several offset time, the bursts are classified according to the offset time and QoS and compete with TDB at equal condition. After competing and bursts grouping process, the bursts will be assigned to wavelength group. By doing so, the QoS level of bursts is the same because the offset time is equal among same wavelength groups.

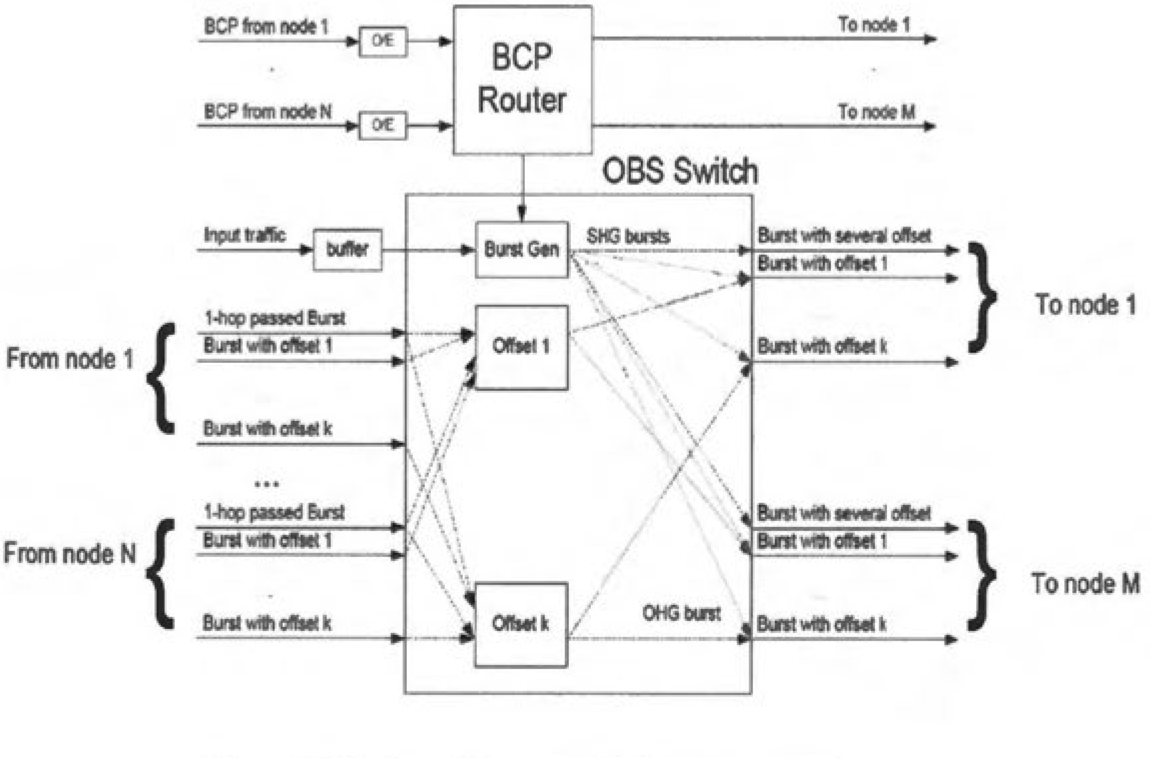


Figure 18. Node architecture of fariness guaranteeing.

3.2 Loss-less DWDM Ring Metro Networks

3.2.1 Edge Core Node Combined Network

In this section, we present the node structure of the proposed LAOBT and how the LAOBT increases link utilization with delay compensation for the slightly increased E2E delay caused by the FDL. Fig. 19 shows the node structure of the LAOBT in a unidirectional WDM metro ring network. The main components of the LABOT are the splitter, FDL, optical add/drop multiplexer (OADM), control logic, and 2×2 OXC per wavelength. The WDM network has N nodes and W wavelengths in a single fiber. In LAOBT, instead of using the control channel, which is commonly used in conventional OBS protocols [3], the burst control information (e.g., source address, destination address, payload length, network management information, etc.) is embedded in the header of the burst and transferred simultaneously through data channels.

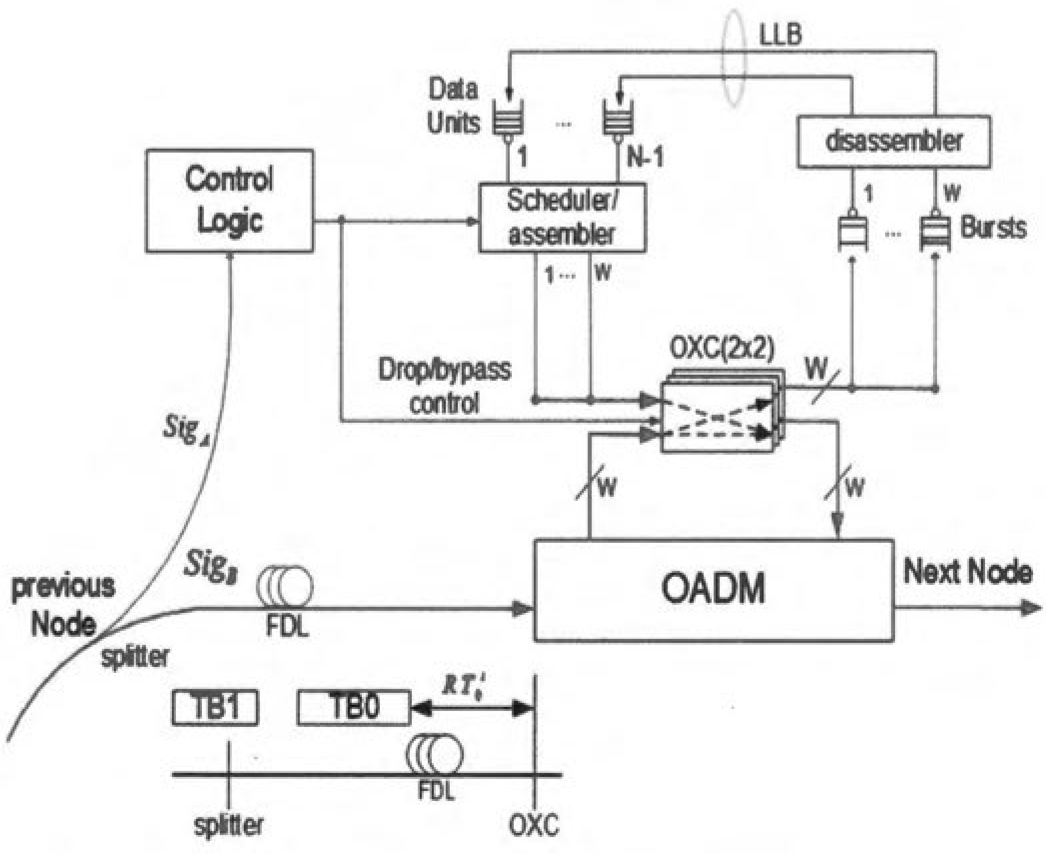


Figure 19. Node Structure of look-ahead optical burst transmission (LAOBT).

Before we describe the LAOBT operation mechanism, we make definitions for several terms. We distinguish bursts as generated bursts (GBs), incoming bursts (IBs), transit bursts (TBs), and arriving bursts (ABs). A GB denotes a burst generated at the current node, and an IB denotes a burst that is incoming from the previous nodes to the current node. Additionally, IBs are classified as TBs, which pass through the current node, and ABs, whose destinations are the current node.

The void indicates the idle interval between TBs, and the void size is the duration of the void. To insert GBs without any contention within the anticipated void between incoming bursts, the control logic must determine the appropriate void size. When an incoming burst arrives at the splitter, the optical signal is split into two at the splitter. One (Sig_A) is used at the control logic and the other (Sig_B) is delayed by the FDL and then dropped/bypassed by the OXC according to the types of IB (i.e., TB or AB). If the control logic detects the arriving burst using Sig_A in advance, it calculates the burst's remaining time to the OXC for each wavelength while Sig_B is being delayed in the FDL as shown in Fig. 20.

In this figure, D_F denotes the fixed time delay by the FDL, TB_0 means the closest TB to the OXC, and RT_0^i is the TB_0's remaining time to the OXC for the *i*th wavelength. If the TB_0 locates at the outside of the splitter as in figure. 20, the maximum void size is same as D_F. Whereas, if the TB_0 locates inside the FDL as in figure. 20 (b), the void size is determined as the RT_0^i for the *i*th wavelength.

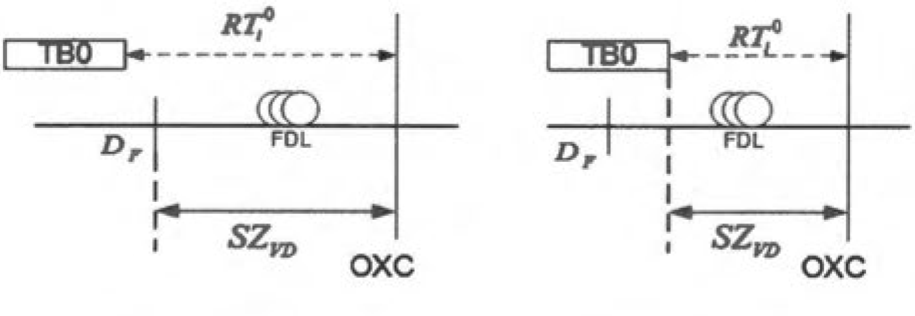


Figure 20. Position of the TBs vs. void size for the *i*th wavelength (LAOBT).

Our insertion-based burst generation scheme uses the FDL to anticipate the void size. To mitigate E2E delay increment by the FDL, we adopt two scheduling schemes for selecting the transmission queue and channels. First, for generating the bursts, we consider the longest queue (LQ) scheme, in which the queue having the largest amount of packets is selected, because the packet waiting time among the queues can be kept small and fair, and the void size can be utilized maximally compared to the round robin scheme. Second, for the channel selection scheme, we choose the Max Void First (MVF) scheduling scheme because a larger void can accommodate more packets. In the MVF scheduling scheme, the largest void size (L_{VD}) is chosen among selected void lengths for each wavelength and limited by D_F as in Eq. (3.1)

$$L_{VD} = \min\left[D_F, \max\left[RT_0^0, RT_0^1 ..., RT_0^{N_W}\right]\right], \tag{3.1}$$

where N_W is the number of wavelengths.

After selecting the appropriate queue and wavelength, waiting packets in the selected transmitter (TX) queue are assembled into a GB and header information is added to the GB. The size of the GB is limited by L_{VD}, so the maximum size of the GB is always less than or equal to D_F. To transmit the GB to the next node, the control logic crosses the OXC and inserts the GB within voids. The insertion-based burst generation scheme allows the TB to pass through the current node without contention with the GB because the GB only uses the TB's residual bandwidth. Also, this scheme leads to higher link utilization than conventional void-filling schemes, which reserve time slot beforehand and have no ability of full bandwidth utilization, whereas this scheme has an ability to anticipate the void size exactly. When IBs arrive at the control logic, IBs are classified according to their destination in advance using Sig_A. If the IB is a TB, the control logic lets the TB pass through the OXC and the TB reaches to the next node. Otherwise, the OXC drops the wavelength during the time interval of the ABs. After that the ABs are disassembled into packets and they are distributed to access networks.

The proposed insertion-based LAOBT scheme has several benefits in terms of delay and contention free aspects. This scheme allows the TB to pass through the current node without contention with the GBs because the GB only uses the TBs residual bandwidth. Besides, this scheme leads to higher link utilization than conventional void-filling schemes, which reserve time slots beforehand and have no ability of full bandwidth utilization, whereas proposed scheme anticipates the void size exactly.

3.3 Implementing Network Architectures

We implement the proposed optical burst switching network in the mesh networks and metro ring networks. For the mesh network, we use our insertion based burst generation scheme in NSF-networks while we use the 4 node metro ring network to implement loss less look ahead burst transmission system. All of the systems are implemented in the computer programming environment.

3.3.1 Mesh Network implementation

We consider two nodes and one links to test network performance in mesh networks. Figure. 21 shows the flow chart of the burst generation scheme in completely class isolation scheme. To increase the network performance, the size of the low class bursts are limited and low class bursts only have base offset time. The reason limiting the size limitation of low class bursts is illustrated in the following chapter in detail. For the high class burst, the extra offset times are assigned to increase the priority.

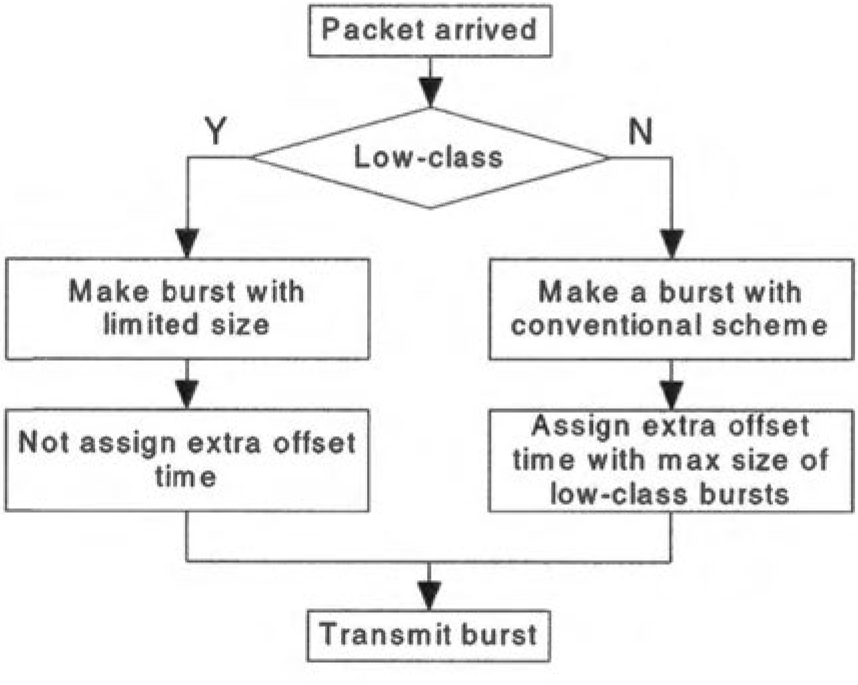
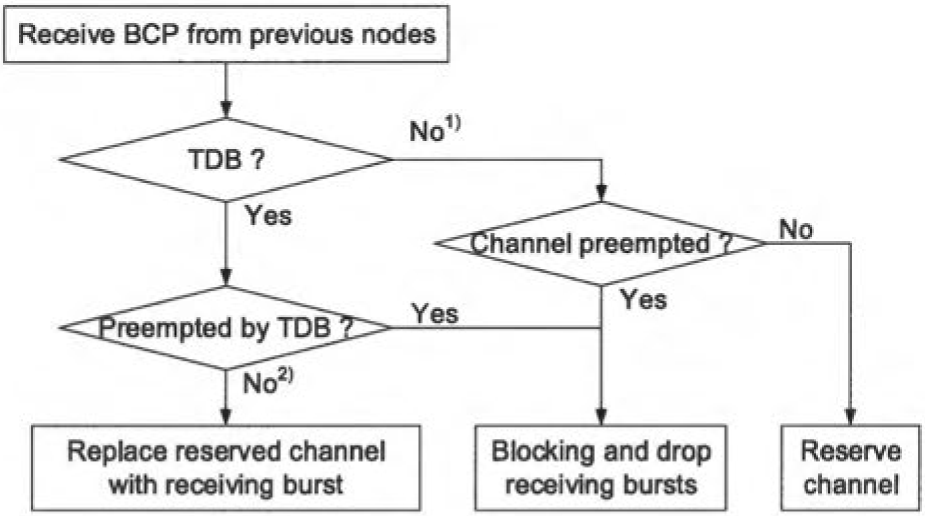


Figure 21. Size based packet assemble scheme.



1) SHG burst arrived

2) Preempted by SHG bursts

Figure 22. Chanel allocation scheme ECNC networks.

In edge core node combined network, the network throughput can be increased by inserting generated burst between transit bursts. Figure. 22 illustrate the channel scheduling scheme for this network. We assign more priority to the transit bursts because these use more network resources. Giving more priority to the bursts which use more network resource is general scheme to increase throughput.

Flow chart in figure. 23 show the implementation scheme of the fairness guaranteeing networks. To increase the network throughput and give more priority to the multi-hop passed burst, the one hop going bursts can be inserted between transit burst and can be transmitted without blocking. In this burst scheduling scheme, the scheduler continuously monitor the arriving of the next control packet. When the control packet is arrived, the burst size of the one hop going burst is determined with the void size. On the other hand, if the next control packet is not arrived, the size of the currently generated one hop going burst is limited to the pre assigned value.

All of the detailed implementation parameters will be explained in the following chapter. For the traffic generation, we consider the exponentially distributed traffic model and self similar traffic mode to represent the real network traffics.

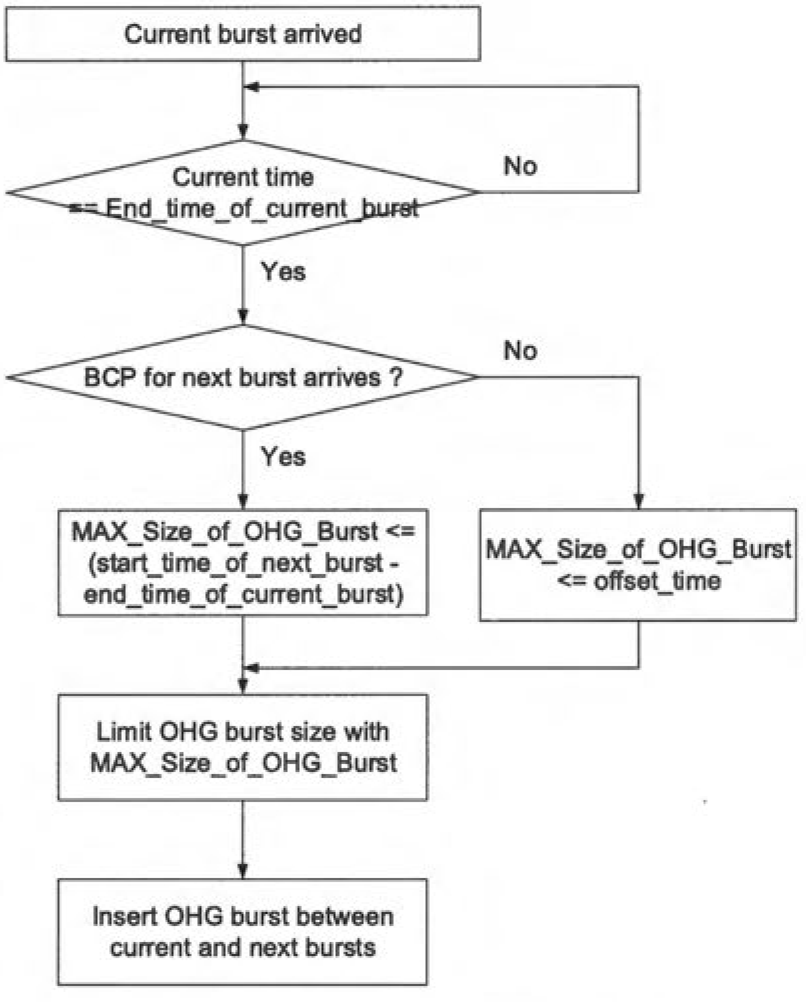


Figure 23. Insertion scheme for one hop going bursts.

3.3.2 Metro Ring Network Implementation

The network structure for the proposed scheme consists of four node in the metro ring networks. To achieve the loss less burst insertion, we consider the calculation of the generated burst as shown in figure. 24. Because the scheduler does not have ability to estimate the arriving burst, the maximum size for the generated burst is limited to the time during of delaying in the fiber delay line as shown in (c) and (d) in figure. 24. However, if the next bursts are located with in the estimation range, the burst size can be exactly calculated. This is illustrated in (a) and (b) in figure. 24.

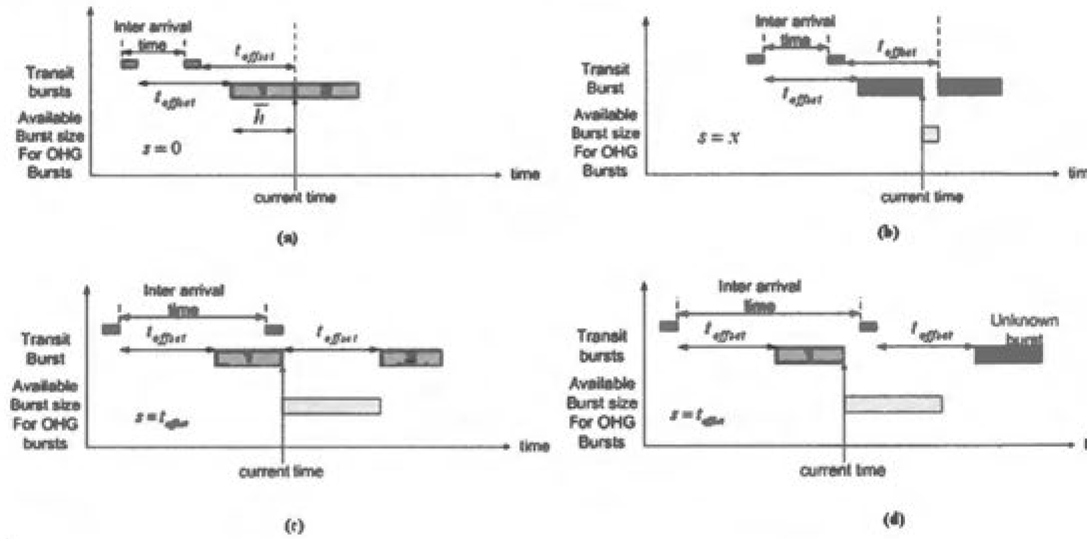


Figure 24. Timing diagram for void size decision.

3.4 Concluding Remarks

In this chapter, we designed the optical nodes for mesh networks and metro ring networks. For the mesh networks, we change the concept of the burst generation. Instead separating core nodes with edge nodes in optical transmission network, the core edge node combined networks is introduced. These nodes have both function of generating bursts and switching bursts. In this network structure, the blocking rate will be decreased compared to the conventional edge core node separated scheme.

We also changed the node architecture to avoid fairness problem in the offset time based QoS priority scheme. By using the concept of the wavelength grouping, the same class bursts are grouped according to the number of remaining node. When every bursts arrive, the wavelength converter change the bursts in terms of the remaining hops to the destination. By grouping bursts, the fairness violation can be avoided.

To implement loss less burst transmission, we drive the insertion based burst generation scheme. By utilizing the void between transit bursts, the generated bursts at the current nodes can be transmitted without collision with the incoming bursts. In designed node, we split the optical signal by using the optical split and fiber delay line to predict the size of the voids between arriving bursts.

To reduce the delay in the Queue, we consider using the immediate burst generation scheme. We drive lots of the burst generation and scheduling scheme to managing wavelength efficiently. This scheme has an advantage of decreasing the waiting time in the transmission queue. Even though this scheme is good at reducing queuing delay, it has a disadvantage of losing the property of the burstness.

The network architecture is implemented to verify our proposed scheme in the mesh and metro ring network. We presented the implementation scheme of scheduling burst and channel allocation mechanism. All of the network elements implemented by using the our own developed computer programming.

In the following chapter, we will discuss the performance analysis by using mathematical theory and simulation tools. The main theoretical formula is the Erlang-B, because the bursts delay in the buffer is not considered. To verify the theoretical analysis, the simulation results will be compared with those of the mathematical results. We use the our own developed C++ programing language instead of the commercialized tools such as NS-3 because this language provide more flexibility to get results.

4 Network Performance Analysis

4.1 JET-based OBS Mesh Networks

In this section, the JET-based OBS networks which use the offset time to differentiate the levels of the priority is considered. It has been shown that the class differentiation in JET OBS networks can be implemented by assigning an extra offset time to the high-class bursts [1, 2, 3]. This offset time based priority scheme is normally applied in mesh networks such as NSF network as shown in figure 16. In section 4.1, all of the performance analysis are performed in the NSF type mesh network. To simplify the network analysis, we only consider two node networks. The end to end network can be extended by using the network assumption. The assumption is that all of the network nodes have the same network environment such as burst arriving rate, inter arrival time, and traffic pattern.

To obtain the performance results, the Poisson traffic generation model is used in this thesis. The benefit of this model is that the simulation results is almost same as that of the theoretical results while the self similar traffic model is different from that of theoretical analysis.

Before describing the JET priority scheme, the parameters used in the following figure are summarized in table 1. In this table, the symbols for offset times of high class and low class bursts, size of bursts, the burst control packet for the bursts and the types of the payload of bursts are illustrated.

Table 1. Parameters used in JET priority scheme.

Parameters	Meaning
α_B	Base Offset Time
α_E	Extra Offset Time
α_H	Offset Time for High-Class Burst s
α_L	Offset Time for Low-Class Bursts
H	BCP for High-class bursts
L	BCP for Low-class bursts
S_{High}	Size of High-class bursts
S_{Low}	Size of Low-class bursts

To illustrate this scheme, we consider a simple two-class OBS network. In figure 25 (a), a high-class data burst and a low-class data burst arrive at node *i* at nearly the same time and desire to be switched to the same outgoing channel.

Since the high-class burst has a larger offset time, its control packet arrives first and successfully reserves the channel. When the control packet of low-class arrives, it sees that the channel has already been reserved. This case can be occurred. Even though the low class bursts arrive before high class burst, the high class burst can preempt channel if the control packet of the high class burst arrives before that of low class bursts. In this way, the high-class burst has implicit priority over the low-class burst.

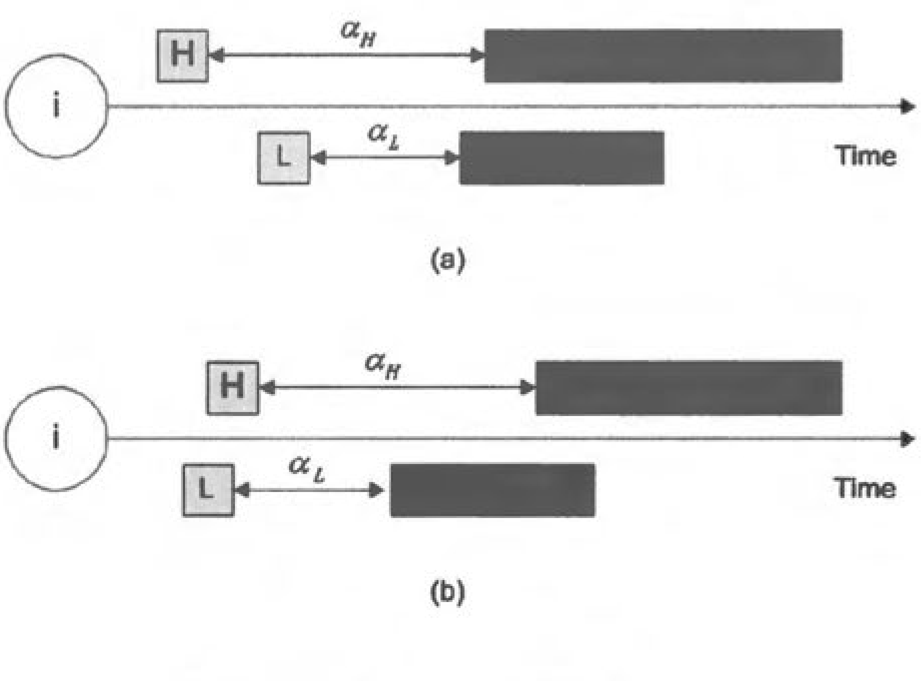


Figure 25. The influence of offset time.

Despite having a shorter offset time, the low-class burst may still successfully reserve the bandwidth if its control packet arrives before the control packet of the high-class burst as in figure 25 (b). However, this event can be made impossible if the offset time of high-class is sufficiently large, in which case the extra offset time is greater than the maximum size of the low-class burst [7].

4.1.1 Burst Transmission Scheme in Completely Isolated Classes

In this section, the burst generation and transmission scheme in completely isolated classes are presented. We define the condition of class isolation degree and analyze the blocking probability of bursts in complete class isolation scheme which is limiting low-class burst size. To verify aforementioned scheme, the performance analysis are conducted by using our own simulation tools implemented C-language.

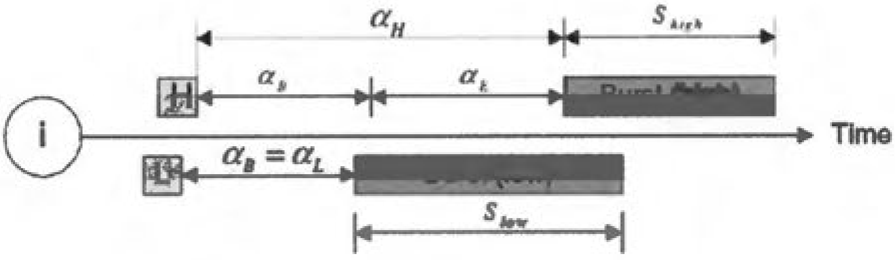
4.1.1.1 Degree of Class Isolation

In JET-based OBS networks, the degree of class isolation is implemented by assigning extra offset time between BCP and DB for the high-class burst. The degree of class isolation is determined by the ratio between extra offset time of high-class burst and length of low-class bursts [7]. Complete class isolation can be achieved when the extra offset time is greater than the maximum size of low-class burst. Therefore, we can draw the condition of complete class isolation as shown in equation 4.1.

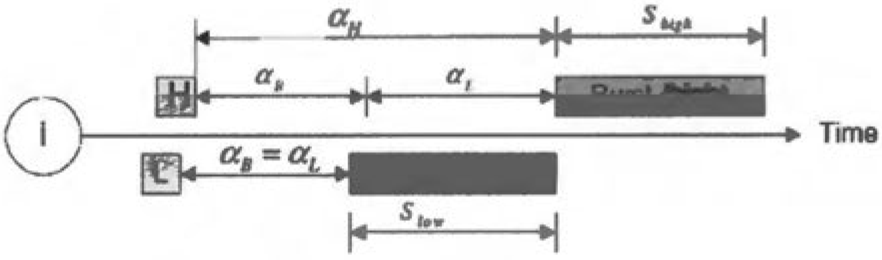
$$\alpha_E \geq \max\left[S_{LOW}\right] \tag{4.1}$$

Figure 26 illustrate the degree of class isolation with the variation of the low class burst size. In figure 26 (a), when the extra offset time is smaller than the maximum size of low-class burst, class isolation is incomplete because the BCP for high-class bursts arrived after the BCP of low-class and the high-class burst arrives before the end of low-class bursts.

In this case, the low-class bursts can affect the blocking rate of high-class burst. But when the extra offset time (α_E) is greater than the size of low-class burst (S_{LOW}), complete class isolation is achieved because the low-class burst can not influence the loss rate of high-class burst even though the BCP for high-class bursts arrives after the BCP of low-class bursts as shown in figure 26 (b) and (c). If class isolation is completed, the law of conservation cannot be applied to calculate low-class blocking probability [2].



(a) Incomplete class isolation



(b) Exact class isolation

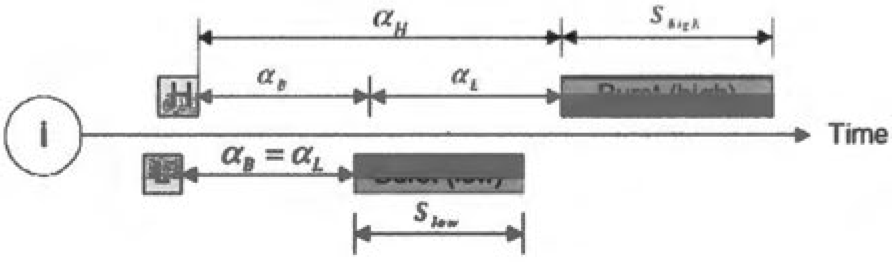


Figure 26. Degree of class isolation.

Table 2. shows some of the corresponding values of extra offset time and the degree of isolation when the distribution of low-class length is exponential. $\overline{L_L}$ means the average length of low-class burst. The degree of class isolation approaches to one as an extra offset time increases. When the isolation degree is one, complete class isolation can be achieved. This situation occurs only when extra offset time is infinite.

Table 2. Degree of class isolation according to the extra offset time.

Extra Offset Time	$0.4 \cdot \overline{L_L}$	$1 \cdot \overline{L_L}$	$3 \cdot \overline{L_L}$	$5 \cdot \overline{L_L}$	$7 \cdot \overline{L_L}$	$9 \cdot \overline{L_L}$
Isolation Degree	0.32968	0.632121	0.950213	0.993262	0.999088	0.999877

4.1.1.2 The Influence of Low-Class Burst Size in Completely Isolated classes

We describe the relation between low-class burst length and its blocking rate more detail. In figure. 27, we describe two cases of low-class data burst traffic in a situation of complete class isolation. In Case I, the length of the low-class data bursts is longer than that of Case II. Because the length of data bursts is large, low-class data bursts have difficulty finding available intervals.

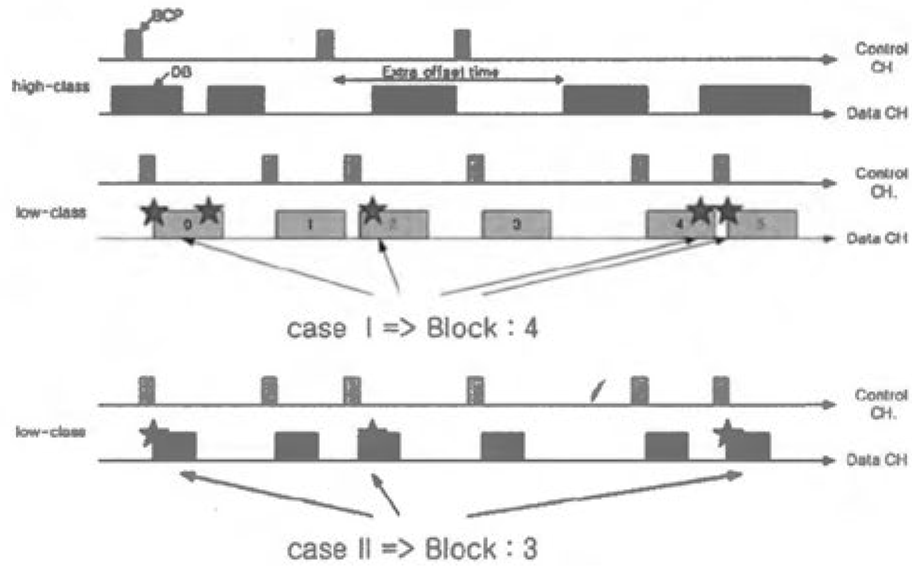


Figure 27. Effect of low class burst length.

Therefore, the resulting blocking number is 4 in Case I. In Case II, the length of the low-class data bursts is shorter than that of Case I. Because of the small data burst length, the low-class data burst easily finds an available interval between preempted high-class data bursts. The number of blocking data bursts in Case II is 3. This is why the length of low-class affects the performance of low-class data burst traffic in the case of the complete class isolation.

In the case of complete class isolation, the blocking probability of high-class burst can be calculated as in Eq. (4.2) using Erlang's loss formula [6], since the low-class burst can no longer have any effect on the high-class performance,

$$B(\lambda, \rho_H) = \frac{1/\lambda! \cdot \rho_H}{\sum_{k=0}^{\lambda} 1/k! \cdot \rho_H} \tag{4.2}$$

where λ denotes the number of wavelength of the link and ρ_H is offered traffic load of high-class data bursts. This means that the wavelength can be exclusively used for high class burst. The remaining bandwidth is only used for low class bursts because low class bursts do not influence the performance of the high class bursts.

By using conservation law as shown in Eq. (4.3), low-class blocking probability can be calculated [2]. Some authors tried to obtain the blocking probability of low-class bursts [2, 3]. In Eq. (4.4), the blocking probability of low-class bursts can be calculated when the blocking probability of total and high-class burst traffic is known.

$$Pb_{tot} = \frac{\rho_H \cdot Pb_H + \rho_L \cdot Pb_L}{\rho_{tot}} \tag{4.3}$$

$$Pb_L = \frac{\rho_{tot} \cdot Pb_{tot} - \rho_H \cdot Pb_H}{\rho_L} \tag{4.4}$$

In the following chapter, the analysis results will be shown and compared with the simulation results.

4.1.2 Burst Segmentation Scheme

In OBS networks with completely isolated classes, to reduce the blocking probability of the low-class burst, one can consider reducing the size of low-class bursts. But by doing so, the number of BCP would be increased. This means that the load of control channel would be increased

If the traffic load of the control channel is increased, it is likely to suffer loss of BCP. This situation will induce a performance degradation of OBS networks. To compensate the aforementioned problem, we propose a segmentation scheme to low-class bursts. As shown in figure. 24, by using the segmentation scheme for low-class bursts, the blocking rate of low-class packets is likely to be decreased.

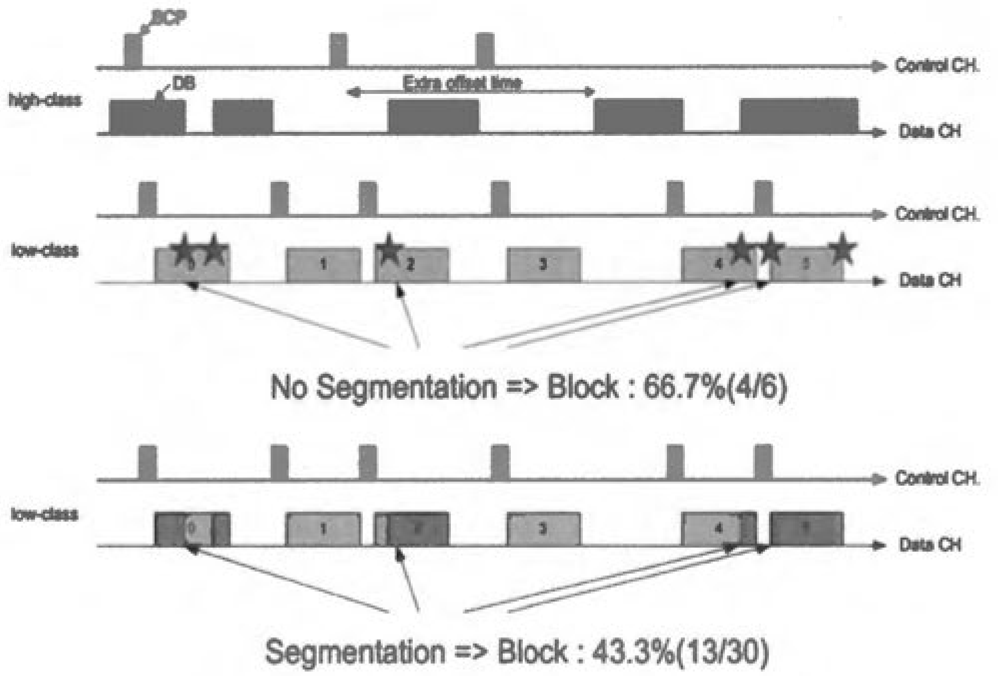


Figure 28. Segmentation scheme for low-class bursts.

There is a close relation between the burst length of low-class and the blocking rate of low-class. If the maximum size of the low-class burst is limited with a small value, the blocking rate of low-class burst is minimized while the traffic load of the control channel is increased. Therefore, to improve loss performance of low-class, we propose of limiting the size of low-class bursts and assign the extra offset time, which is used for QoS differentiation, with the maximum size of low-class bursts. The maximum burst size of low-class and the extra offset time of high-class burst are set by the OBS network operator. By doing so, complete class isolation can be achieved

4.1.2.1 Blocking Analysis for piggy backing

The piggy backing scheme can increase the performance of the specific class of information with the tradeoff of the degradation of the remaining information. Fig. 29 shows an example of the piggy backing scheme in the classified priority scheme. In this scheme, only high class packets can be piggy backed to the following burst. By doing this, the blocking rate of the higher class packets can be decreased while that of the lower class burst would increase.

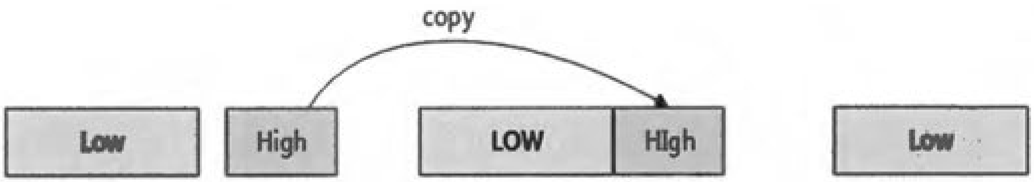


Figure 29. Piggy backing in priority scheduling.

In this section, the blocking probability of the packets in a burst is analyzed by using the Erlang traffic model. To analyze the performance easily, the one link networks are considered. Because of the bufferless property of OBS network, the erlang-B model can be thought of. The typical erlang-B loss formula can be expressed as equation (4.5). In this equation, the blocking rate can be obtained by using the traffic load (ρ) and the number of wavelength (c). By using equation (4.5), the blocking rate of the class-less burst can be calculated in OBS networks [6].

$$P_B(c,\rho)=\frac{\frac{\rho^c}{c!}}{\sum_{k=0}^{c}\frac{\rho^k}{k!}} \tag{4.5}$$

In this section, the blocking probability of the packets in a burst is analyzed by using the Erlang traffic model. To analyze the performance easily, the one link networks are considered. Because of the bufferless property of OBS network, the erlang-B model can be thought of. The typical erlang-B loss formula can be expressed as equation (4.5). In this equation, the blocking rate can be obtained by using the traffic load (ρ) and the number of wavelength (c). By using equation (4.5), the blocking rate of the class-less burst can be calculated in OBS networks.

Before driving the analytical results for the piggy backing model, we can draw the blocking rate for the priority queuing model. By using the conservation law, the blocking rate of the high class burst and low class burst can be obtained. For the high priority class, the blocking rate can be calculated by using equation (4.6). In priority model, the low class bursts do not influence the high class burst in terms of blocking rate. So the blocking rate of the high class burst can be calculated by using the number of capacity and the traffic load of high priority bursts (ρ_H). The high class burst is considered to use all of the channel its own traffic.

$$P_B^H(c,\rho_H) = \frac{\dfrac{\rho_H^k}{c!}}{\sum_{k=0}^{c} \dfrac{\rho_H^k}{k!}} \tag{4.6}$$

Regarding the calculation of blocking rate for the low class, the conservation law can be used as shown in equation (4.7). Because of the property of the equilibrium of the product of load and blocking rate, the product of total load and blocking rate of total traffic load is equal to the summation of each product of traffic load and blocking rate for high and low class burst. By changing this equation simply, the blocking rate of low class burst can be calculated by using the blocking rate of high class burst and blocking rate of total traffic road.

$$\begin{aligned} &\rho_{Tot} \cdot P_B(c,\rho_{Tot}) = \rho_L \cdot P_B^L(c,\rho_L) + \rho_H \cdot P_B^H(c,\rho_H) \\ &P_B^L(c,\rho_L) = \frac{\rho_{Tot} \cdot P_B(c,\rho_{Tot}) - \rho_H \cdot P_B^H(c,\rho_H)}{\rho_L}, \\ &where \rho_{Tot} = \rho_H + \rho_L \end{aligned} \tag{4.7}$$

Before calculating blocking rate in the piggy backing model, we assume that all of the high class packets are piggy backed to increase the performance. First of all, we can calculate low class burst by using the conservation law as shown in equation (4.8). Because the high priority packets are piggy backed, the total traffic would be increase with the amount of (ρ_H).

The total traffic volume increase to $\rho_{tot}^P = \rho_H + \rho_H + \rho_L$. With this traffic volume and the number of wavelength, the blocking rate of low class burst can be obtained. The blocking results of the priority model can be reused to draw this conclusion. The results of blocking rate of total and original high class burst are used to obtain the blocking rate for the low class burst. So the blocking rate of the low class burst can be easily obtained by using the information of the previously calculated results. This is the main achievement of the thesis by considering the blocking conservation law.

$$P^L_{piggyback} = P^L_B\left(c,\rho^P_L\right) = \frac{\rho^P_{tot}\cdot P_B\left(c,\rho^P_{tot}\right) - \rho_H \cdot P^H_B\left(c,\rho_H\right)}{\rho^P_L},$$
$$where \rho^P_{tot} = \rho_H + \rho^P_L,$$
$$\rho^P_L = \rho_H + \rho_L \tag{4.8}$$

The blocking rate for high class packet can be obtained by subtracting non-blocking rate from one. The probability of reaching destination node successfully is $\left(1-P^H_B\left(c,\rho_H\right)\right)$ for the packets in the original busts.

When the original bursts are dropped due to the contention with the probability of $P^H_B\left(c,\rho_H\right)$, the packets in the original burst have another opportunity to contend channel in the piggy backed bursts with the priority of $\left(1-P^L_B\left(c,P^P_L\right)\right)$. The blocking rate for low class bursts in this equation can be used in equation (3.3). The final blocking rate of high class packets is drawn as equation (4.9).

$$P^H_{piggyback} = 1 - \left[\left(1-P^H_B\left(c,\rho_H\right)\right) + P^H_B\left(c,\rho_H\right)\cdot\left(1-P^L_B\left(c,P^P_L\right)\right)\right] \tag{4.9}$$

The blocking rate for high class packet can be obtained by subtracting non-blocking rate from one. The probability of reaching destination node successfully is $\left(1-P^H_B\left(c,\rho_H\right)\right)$ for the packets in the original busts. When the original bursts are dropped due to the contention with the probability of $P^H_B\left(c,\rho_H\right)$, the packets in the original burst have another opportunity to contend channel in the piggy backed bursts with the priority of $\left(1-P^L_B\left(c,P^P_L\right)\right)$.

The blocking rate for low class bursts in this equation can be used in equation (4.9). The final blocking rate of high class packets is drawn as equation (4.9). By using the equation (4.8) and (4.9), the blocking rate for the low class and high class burst can be drawn with the input parameters of the number of wavelength and normalized traffic load.

So the blocking rate of the low class burst can be easily obtained by using the information of the previously calculated results. This is the main achievement of the thesis by considering the blocking conservation law.

4.1.3 Fairness Guaranteeing Scheme

In this section, we analyze the network performance for the fairness guaranteed mesh networks presented in the previous chapter. Firstly, we consider network throughput as the channel utilization of the wavelength groups and assume traffic load is equally distributed among wavelength group. By using the well-known Erlang loss formula [6], the carried traffic to the wavelength group can be calculated by using Eq. (4.10) when the burst arrival pattern is Poisson distribution and the burst size is distributed exponentially.

$$\rho_c = \rho_o \cdot [1 - Pb(\rho_o, k)] \tag{4.10}$$

where, ρ_o is offered load of TDB to the wavelength group and k is the number of output channels for wavelength group. Therefore, the throughput for the wavelength group for specific offset times can be calculated by using Eq. (4.11).

$$H_T = \rho_c / k \tag{4.11}$$

There are several researched to utilize the void interval between bursts [9, 12]. If the information contained in BCP is used appropriately, the network utility will be improved dramatically. Ideally, OHG bursts can utilize the remaining bandwidth of output channels if OHG bursts were inserted fully in the void intervals between TDB. In this case, the available maximum throughput of the OHG bursts can be calculated by Eq. 4.12 and 4.13.

$$\rho_{in}^{\max} = 1 - \rho_c \tag{4.12}$$

$$H_{in}^{\max} = \rho_{in}^{\max} / k \tag{4.13}$$

To enhance the throughput of ECNC, we proposed the void filling scheme for OHG bursts which means that OHG bursts are inserted between void intervals of TDB. If this scheme is used for mesh network, the total throughput will be increase without effect the performance of the TDB. The void filling scheme is illustrated in figure. 30. By using the property of OBS network, we can estimate the available void intervals among TDB exactly, which is the available size of OHG bursts, by using the information contained in BCP.

By using the property of OBS network, we can estimate the available void intervals among TDB exactly, which is the available size of OHG bursts, by using the information contained in BCP. By using the Eq. (4.14), the available burst length of OHG can be calculated exactly as a function of offered load and offset time of transit bursts based on the assumption of equal distribution of offered traffic load to every wavelength groups.

We can drive Eq. (4.14) by dividing void intervals of the transit burst into two regions as illustrated in figure. 30:

$$\overline{h_{in}} = f(t_{offset}, \rho_c^{each}) = \int_0^{t_{offset}} x \cdot p(x)dx + \int_{t_{offset}}^{\infty} t_{offset} \cdot p(x)dx \tag{4.14}$$

where, $p(x)(\widehat{u^{each}}e^{-\widehat{u^{each}}x} \cdot dx)$ is probability that void interval is x, x is the length of void interval, $\widehat{u^{each}}$ is termination rate of void interval for each channel, t_{offset} is offset time of TDB, and ρ_c^{each} is the traffic load of TDB for each channel, respectively.

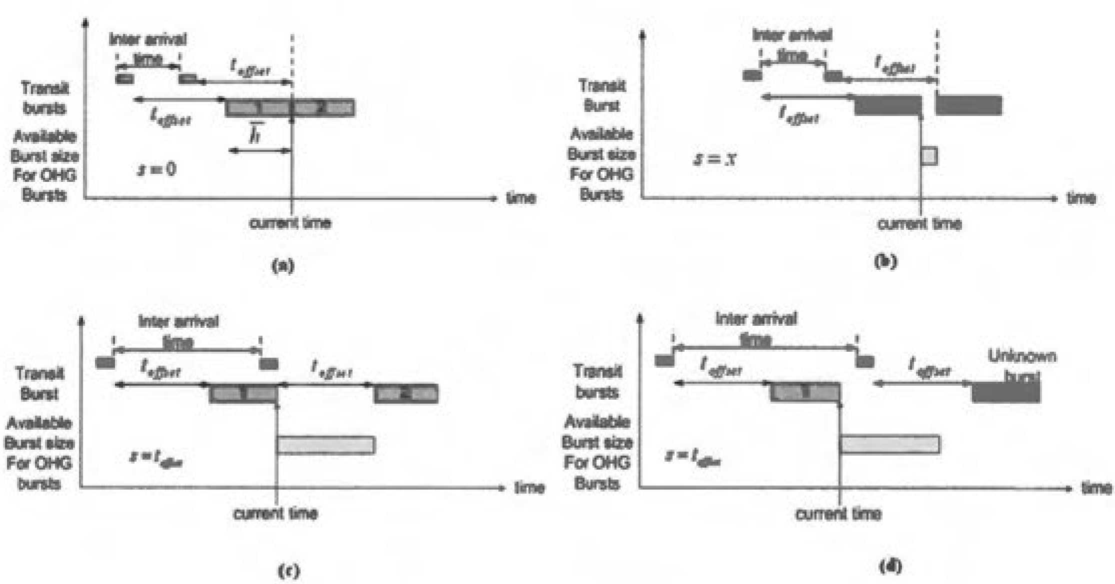


Figure 30. Void-filling scheme for OHG bursts.

When the length of void intervals is larger than the offset time of the TDB, the size of OHG bursts can not be longer than the offset time of TDB because the input nodes do not know the arrival time of the next burst at current time as illustrated in figure. 30 (d).

Therefore, if the void interval is greater than offset time of TDB or the BCP do not arrive at the end of current DB, the burst length of the OHG bursts should be limited to the size of offset time. Otherwise, the TDB will be dropped when the assigned length of OHG is larger than the offset time of TDB and the BCP of TDB arrives immediately at the end of current DB.

After calculating the mean length of OHG bursts, the available throughput for OHG bursts can be calculated by using Eq. 4.15 and 4.16. The traffic load of the incoming traffic can be calculated by producing average burst length and arrival rate. The arrival rate can be obtained with the function of mean length of burst and offered traffic load as in Eq. 4.15. For the throughput, the normalized throughput can be obtained by dividing incoming traffic load with number of wavelength.

$$\rho_{in} = \overline{h_{in}} \cdot v = \overline{h_{in}} \cdot \left(\frac{\rho_c}{\overline{h}}\right) \tag{4.15}$$

$$H_{in}^{available} = \rho_{in}/k \tag{4.16}$$

where h means burst length of TDB.

And the gain acquired by using void filling for OHG bursts can be calculated in Eq. 4.17.

$$G = \frac{H_{in}^{available} + H_{in}^{\max}}{H_{in}^{\max}} \tag{4.17}$$

The gains can be obtained by considering the throughput of the available throughput. This available throughput is added to calculate the network gains. This equation shows that the proposed insertion based scheme have a large network grain compared to the non insertion burst generation scheme.

4.2 Loss-less Metro Ring Networks

4.2.1 Look Ahead Optical Burst Switching

In this section, we analyze the network performance in our designed look ahead burst transmission system in metro ring network as shown in figure 19. Our proposed look ahead burst transmission scheme is only possible in ring network with association of the delay devices such as fiber delay line. In section 4.2, we only consider the ring network and analyze the network performance by considering burst insertion in ring nodes.

Also, we evaluate the performance of the proposed scheme with the BRR statistical TDM (BRR STDM) scheme [20] in terms of the E2E packet delay, delay at the TX queue, and link throughput.

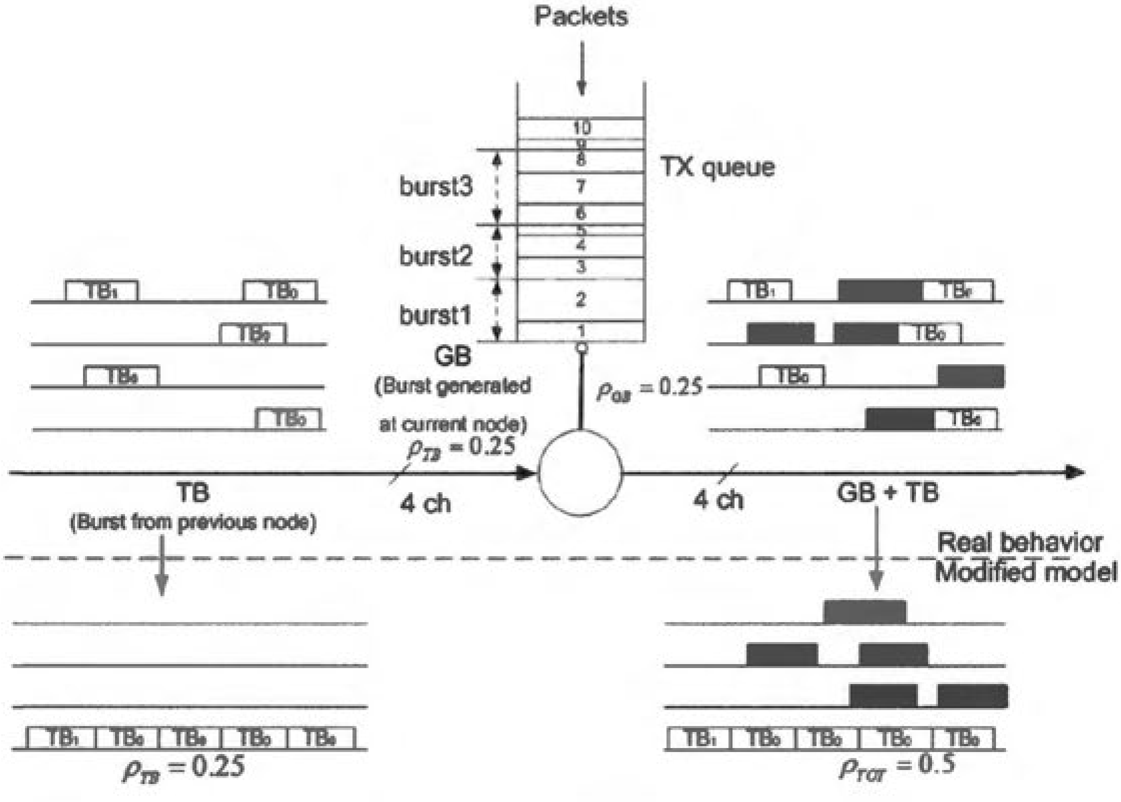


Figure 31. Real VS. modified burst generation in LAOBT.

To analyze the packet's waiting time at the TX node, which is the elapsed time from the packet's arrival to the burst's departure at the edge nodes, we illustrate the bursts' behavior as shown in figure. 31. As TBs cut through the current node, we assume that the TBs preempt the exclusive wavelengths in advance and the GBs use residual bandwidth to transmit bursts. As a result, the number of available channels for the GB, *WGB*, is given by

$$W_{GB} = (1 - \rho_{TB}) \cdot N_W \quad , \tag{4.18}$$

where W_{TB} is the normalized traffic load corresponding to the TBs, and *NW* is the number of wavelengths. Then, we define the normalized traffic load by W_{GB} for the GB, _M GB, as follows.

$$\rho_{GB}^{M} = \frac{N_W}{W_{GB}} \cdot \rho GB \quad , \tag{4.19}$$

where $\_{GB}$ is the original traffic load corresponding to the GBs.

In the optical burst transmission system, the delay at the TX node consists of the packet assemble time, the burst waiting time for an available channel, and the burst transmission time. First, to obtain the packet assemble time, *TA*, which is the time to aggregate waiting packets into a burst, we assume that the packets are virtually grouped into a burst as shown at the TX queue in figure. 28 and the packet arrivals follow the Poisson process. Because the 1st packet in a burst does not have assemble time delay, we only investigate the assemble delay for the 2nd and the following packets. By applying these assumptions, *TA* can be approximately obtained by multiplying the packet's waiting time before assembling and the existence probability of each packet in a burst, and finally summing waiting times of each packet, as appeared in the 2nd term inside the parentheses in Eq. (4.20). The 1st term in the parentheses is added to calculate assemble time when the mean number of packets contained in a burst is not an integer value.

$$T_A = \left(\frac{\left(N_B^{pkt} - \left\lfloor N_B^{pkt} \right\rfloor \right)}{N_B^{pkt}} \cdot \left(N_B^{pkt} - 1 \right) + \frac{1}{N_B^{pkt}} \cdot \sum_{k=1}^{\left\lceil N_B^{pkt} \right\rceil} (k-1) \right) \cdot \bar{t}_{IA} \quad , \tag{4.20}$$

where t_{IA} is the mean packet inter-arrival time to the edge node and N_{pkt} *B* is the average number of packets contained in a burst as follows.

$$N_B^{pkt} = 1 + \frac{\sum_{k=N_W+1}^{\infty} k \cdot P_k}{N_W} \quad (4.21)$$

In Eq. (4.21), *Pk*, based upon M/M/c for arriving packets, is the probability when the edge node has k packets. Also, because bursts contain more than one packet, the 2nd term, the average number of waiting packets in the queue for each wavelength, is added.

Second, by applying the number of wavelengths and traffic load acquired by Eq. (4.22) and Eq. (4.23) to the M/M/c queuing model [8] for bursts, we can obtain the average waiting time of the GB, *TQ*, which is the summation of burst waiting time and burst transmission time, as following Eq. (4.21).

$$T_Q = \frac{\overline{h} \cdot N_B^{pkt}}{W_{GB} \cdot \rho_{GB}^{M}}, \quad (4.22)$$

where *h* is the mean burst length as follows.

In Eq. (4.22), *TOH* and *b* are time required for the bursts' overhead and average packet length, respectively. Therefore, the total delay in the TX node, *Ttot*, is expressed as the summation of Eq. (4.22) and Eq. (4.23).

$$T_{tot} = T_A + T_Q \quad (4.23)$$

Eq. (4.23) is verified by comparing with simulation results when the number of wavelength is 16.

We also propose a traffic predictive burst generation scheme to increase the data content in a burst without deteriorating the queuing delay. Between the time limit and burst size limit, we consider the network predictive time control scheme by using several parameters as shown in Eq. (4.24). The reason why we use this scheme is that the immediate burst generation scheme in the previous discussion tends to lose the property of burstness. By changing the timeout value, the number of packets in a burst can be sustained almost constants. To obtain the function and the influencing parameters, we performed simulation for the traffic changes. The parameters influencing the timeout value are the time value needed for delaying optical signal in FDL, t_{FDL}, estimated traffic normalized load in the network, load, time length of data unit, t_{DU}, and the size of back log in the transmission queue, t_{TxQue}:

$$TimeOut = f(t_{FDL}, load, t_{DU}, t_{TxQue}) \tag{4.24}$$

Time length of optical signal in FDL is considered for inserting the generated burst between transit bursts. Traffic load is used to change the generated burst size adaptively based on the traffic. In light traffic, the timeout value tends to increase to accommodate almost same amount of data unit as that of heavy traffic load. By doing this, the characteristic of burstness can be sustained. Equation (4.25) shows a possible example of such function, where, f_Q is a function of transmission queue size, Lq. When the size of the queue is large, the output would decrease and it controls roll-over time horizon. This makes the burst short and avoids the overflow of the queue where load is the normalized traffic load.

The value of α ranges in the interval 5 to 10 and it is determined experimentally. The timeout value tends to be short when the traffic load is heavy while that of light load tends to be large to accommodate many packets. This mechanism determines the volume of data content in the burst according to the adaptive traffic volume.Additionally, the data unit size and size of FDL determine the timeout value. This can be possible by selection minimum value between the values calculated by adaptive traffic scheme and FDL size. The final value of time out can be decided by the minimal value between $f_Q\left(t_{TXQue}\right)\cdot\frac{\alpha}{load}\cdot t_{DU}$ and t_{TxQue}, which limit the burst size with the time respect to delay for the optical signal in FDL. Limiting the generated burst size by t_{TxQue} enables the LLB bursts to be inserted between transit bursts.

$$TimeOut = \min[f_Q(t_{TxQue}) \cdot \frac{\alpha}{load} \cdot t_{DU}, t_{TxQue}] \tag{4.25}$$

By applying this scheme, the number of data units in a burst increases under light traffic load condition while keeping in control the waiting time in the queue.

4.3 Concluding Remarks

In this chapter, we performed the analysis of the network we proposed in mesh network and metro ring networks. Several assumption and network models are presented to analyze the network performance mathematically.

First of all, we drive the equation for the blocking probability in mesh network in the priority class scheme by using the Erlang-B formula. The comparison between completely isolated class and segmentation is also presented. The performance of the segmentation scheme is analyzed mathematically and show that segmentation scheme is better than that of conventional scheme.

One of the blocking reduction scheme, we introduce the scheme of piggybacking and analyze the blocking rate for the priority class by modifying the Erlang-B to our network model. For the throughput in fairness guaranteed network, the throughput of the network is driven successfully.

For the delay analysis in the lossless metro ring network, we can drive the mathematical formula by introducing the virtual queuing system. By using this assumption, the delay in the queue and the throughput is calculated. To calculate the void size in the look ahead burst transmission system, we analyze the relationship between the arriving burst and the fiber delay line. We can predict the maximum burst size generated in the current node.

To sustain the burstness property in look ahead burst transmission scheme, we introduce the traffic adaptive burst generation scheme. This scheme is useful in terms of maintaining the number of packets in a burst regardless of the traffic load. We determined the size of the burst by considering network volume and drive the equation for the burst size.

In the following chapter, we will present the analysis results and interpret the meaning of the analysis results by using the simulation results and the lots of figures. We already have a simulation test bench implemented by C++ computer programming language.

5 Interpretation of Analysis Results

This chapter consists of two part. In the first section, the mathematical analysis results and simulation results for the mesh network is presents. The meaning of the graph is also interpreted.

In the other section, the analysis results of the metro ring network is presented and interpreted. Due to the property of the loss less burst transmission, the interpretation of the delay and the network throughput are presented. All of the simulation is performed by using our own developed simulation tool.

5.1 Analysis of OBS Mesh Networks

5.1.1 Compete Class Isolation Networks

Before analyzing the blocking rate of the completely isolated class, we investigate the blocking rate by using the conservation law. Some researchers applied conservation law of blocking rate to analyze the relationship between low class and high class bursts.

Figure. 32 shows the blocking probability of low-class and high-class burst by using the conservation law when the wavelength is 4. But, in the case of the complete class isolation, the blocking probability of low class cannot be the same result shown in figure. 32. In this scheme, the low class burst can influence the blocking rate of the high class burst. Additionally, the overall blocking rate can be obtained mathematically by using the low class and high class blocking rate as well as traffic load.

However, if class isolation is completed, the law of conservation cannot be applied to calculate low-class blocking probability. This means that the performance of low class burst can only be obtained by simulation. The behavior of the low class burst will be dealt with in the following example.

Now, we analyze the effect of low-class burst size on blocking probability in complete class isolation by simulation tools. To make our simulation model as simple as possible, we consider a system with a single switch and a single output link. Bursts of all class arrive according to a Poisson process, and the length of high-class bursts is uniformly distributed from 160Kbits to 400Kbits. For each simulation, one hundred million bursts were simulated. The traffic ratio of low-class and high-class is 8:2.

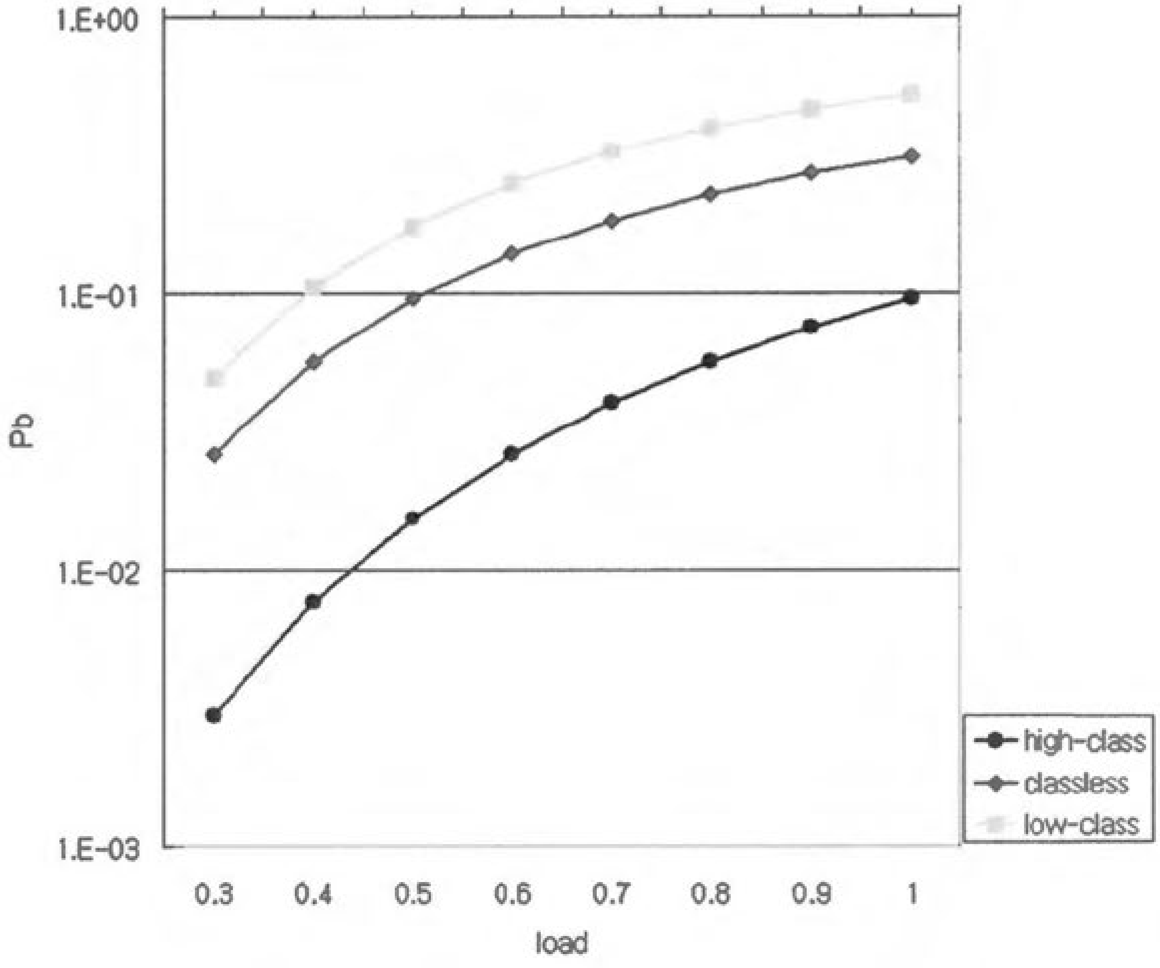


Figure 32. Blocking probability according to the conservation law.

Table. 3 shows the parameters used in this simulation. Figure. 33 shows the simulation result as a function of offered load. The upper dotted lines show that there is performance improvement in low-class traffic as the length of low-class bursts decreases. The lower lines show that the variation of the high-class performance is small at the high offered load. But, at the region of the low offered load, there is some blocking probability variation for high-class bursts. This simulation result can be corrected if a sufficient number of bursts are simulated. The reason of performance improvement on low-class burst is that there are more opportunities to find available interval when the size of the low-class data burst is small.

Table 3. Simulation parameter for completely isolated class.

Value	Description
10 Gbps	Link Bandwidth
160 K bit	Minimum length of high-class data burst
400 K bit	Maximum length of low-class data burst
40 ms	Extra offset time
10^5	Number of simulated bursts
4	Number of channels
2 : 8	Traffic ratio of between high and low class burst

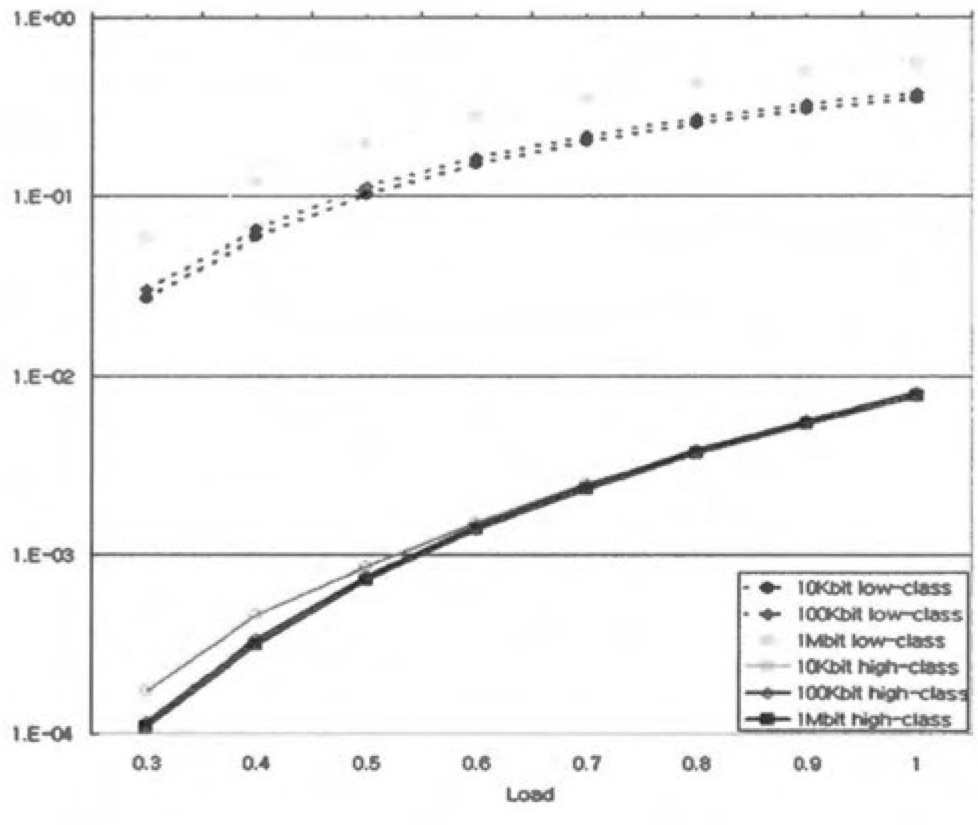


Figure 33. Blocking probability with variation of the size of low class bursts.

Figure. 34 shows the blocking probability of low-class burst as a function of hops when the offered load is 0.7. The end-to-end blocking probability along a path spanning H hops can be expressed as $1 - (1 - P_b)^H$. Fig. 35 shows the blocking probability variations when the ratio of high-class and low-class burst length changes. The analysis and simulation results show that the blocking probability of high-class bursts remains same when the low-class burst size increase. But simulation result of blocking probability of low-class increases as the size of low-class bursts increases.

Figure. 36 shows the relation between conservation law result and simulation result for the low-class burst as a function of normalized class length ratio. The results imply that conservation law does not apply to obtain blocking probability of low-class bursts in completely isolated OBS systems.

As expected, the blocking probability of simulation is lower than analytical result in the region, in which the normalized burst ratio is below 0.5. But in the region above 0.5, the blocking probability of simulation is larger than that of reservation. If the Fiber Delay Line (FDL) were used for burst buffering in completely isolated OBS system, the system performance would be enhanced more. This result shows that the conservation law does not apply anymore in the completely isolated class and the performance can be obtained by simulation.

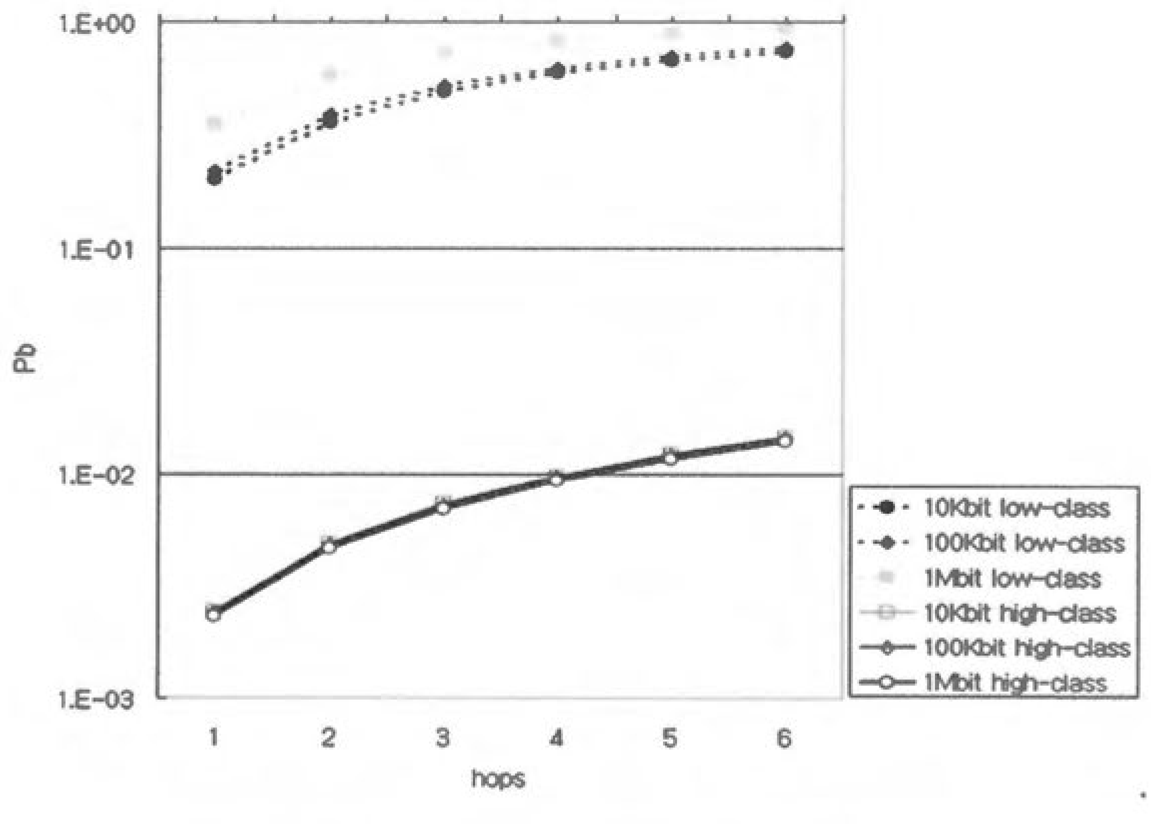


Figure 34. End-to-end blocking probability as a function of hops.

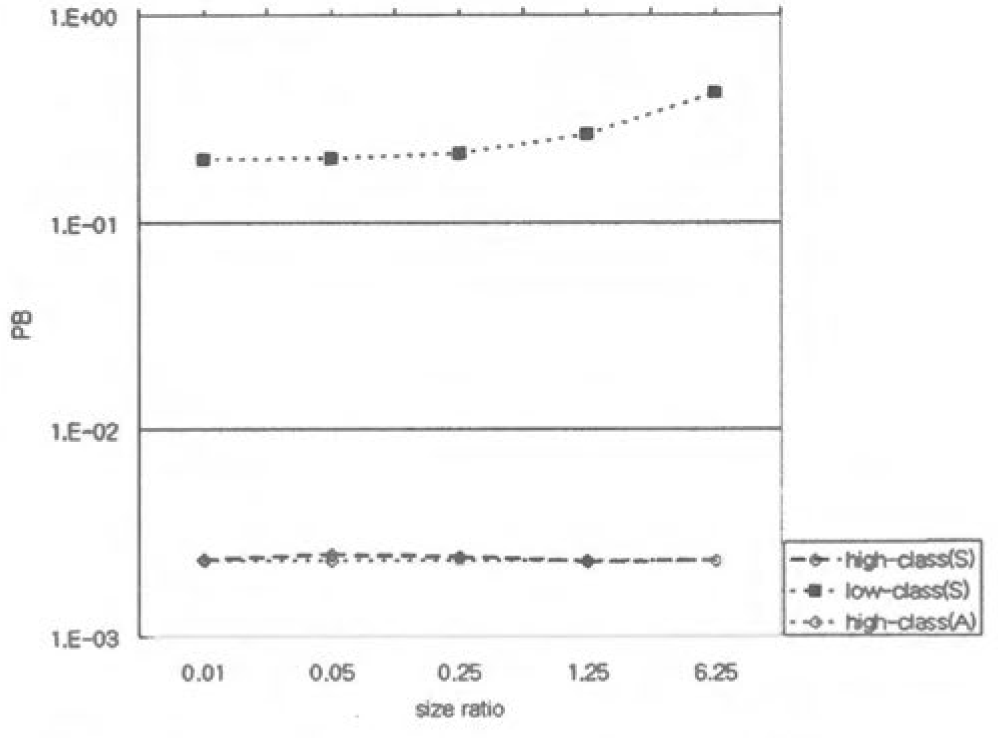


Figure 35. Variation of the normalized low-class bursts size.

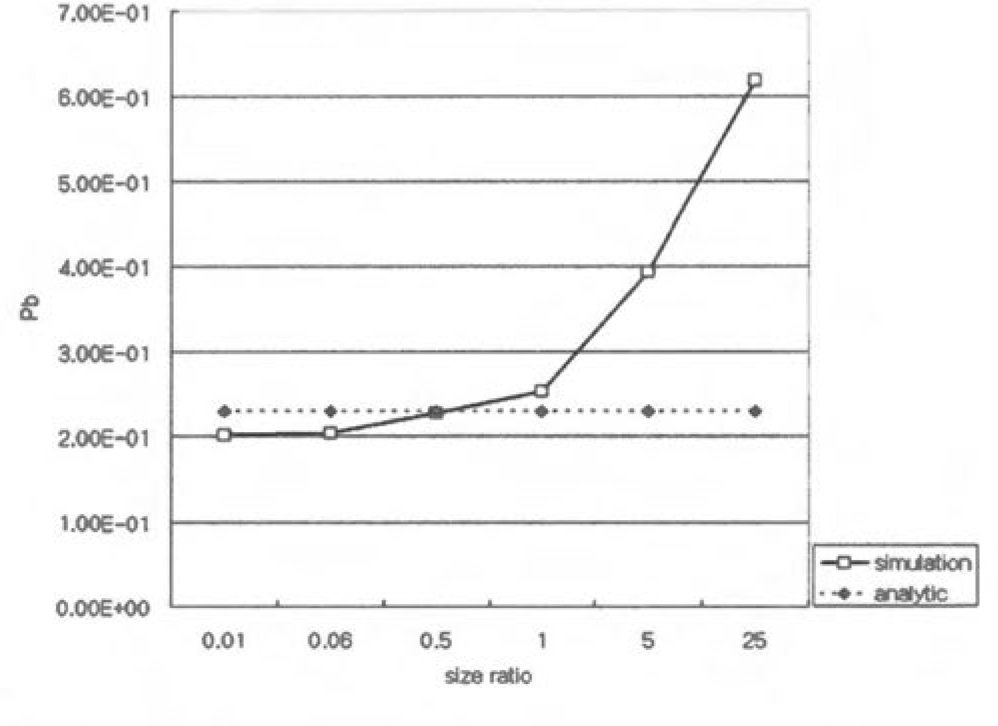


Figure 36. The comparison between simulation and reservation law.

To investigate the effect of extra offset time on the blocking probability of low-class bursts, we change the normalized offset time. Fig. 37 shows the simulation results of low-class burst as a function of normalized extra offset times when the offered load is 0.7. The simulation results show that the optimal loss performance can be obtained when extra offset time is 1, .i.e, the extra offset time is the same as the size of low-class burst.

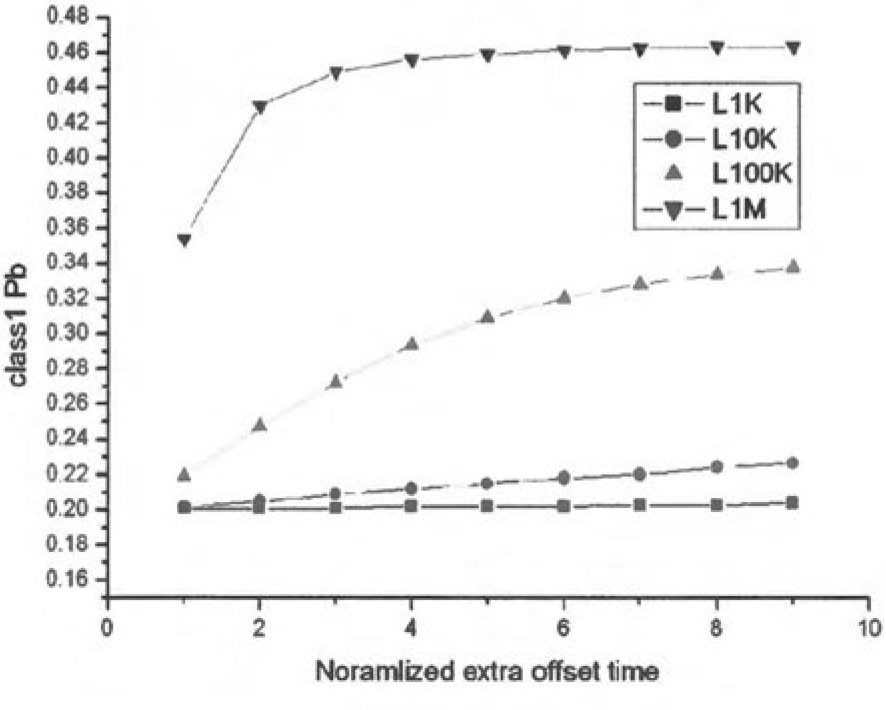


Figure 37. Relationship between normalized extra offset time.

5.1.2 Analysis for the Burst Segmentation

Figure. 38 illustrates the simulation results of packet blocking rate of low-class bursts when applying segmentation scheme with the variation of low-class burst size. In this figure, the packet blocking rates were reduced when segmentation scheme was used. The gain of segmentation is 5dB for low class burst when the low class burst size is 100k bit and offered load is 0.7 Erl/Channel.

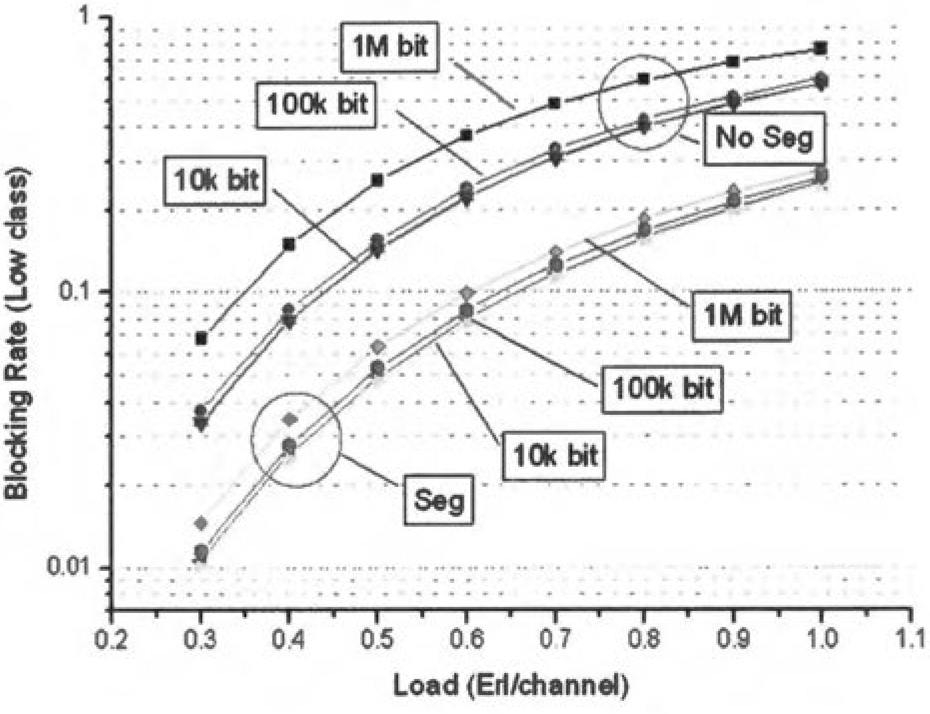


Figure 38. The simulation result between segmentation and no segmentation.

Figure. 39 shows the throughput for segmentation scheme and no segmentation scheme with the variation of low-class burst size, respectively. The simulation results show that, by applying segmentation scheme, the throughput for the OBS network increase great. The throughput obtained in this simulation could be obtained by using Eq. (5.1).

$$Throughput = \frac{time\_occupied\_by\_sucessful\_transmitted\_packet}{total\_siumlation\_time} \tag{5.1}$$

The results imply that, by using the segmentation scheme in low-class bursts, it is not necessary to have a large number of BCP to improve loss performance of low-class bursts. If the number of BCP increases, the traffic load of the control channel also increases, and this will introduce loss of control packets. Therefore, by applying the segmentation scheme in low-class bursts, the blocking probability can be reduced and the number of control packets does not increase.

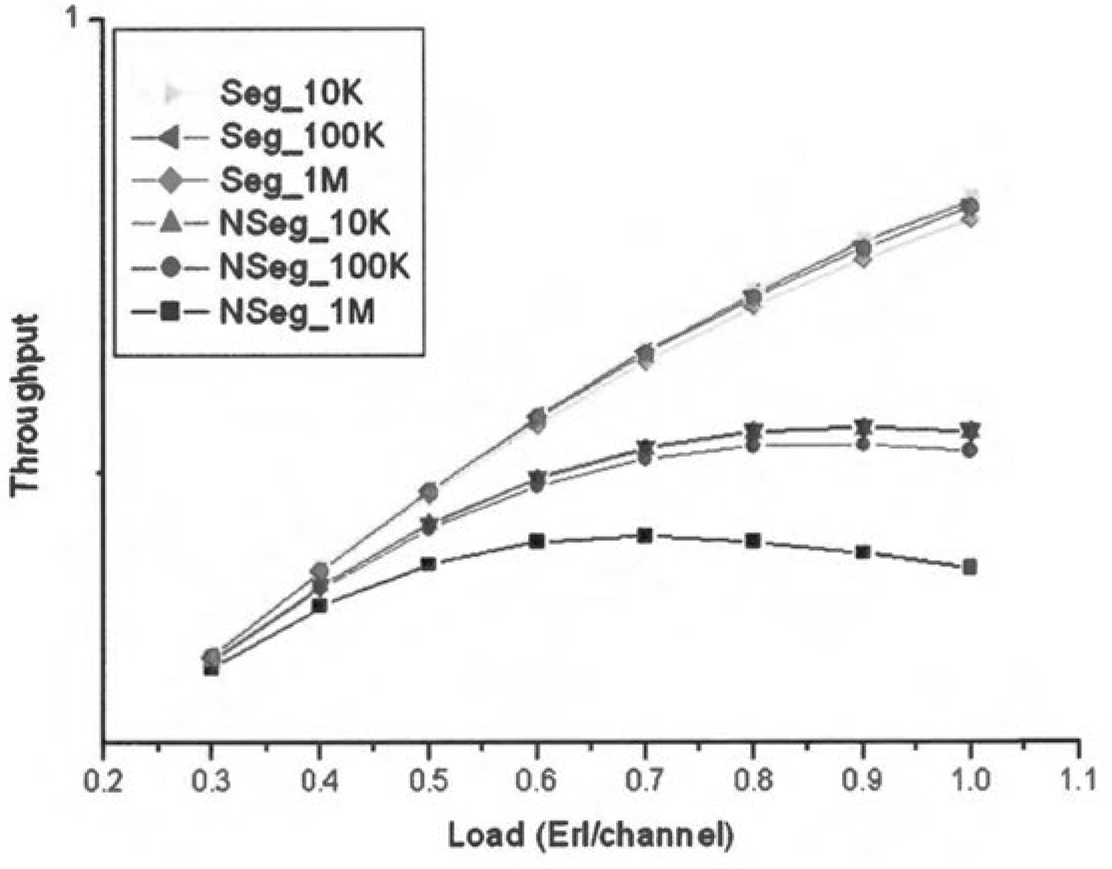


Figure 39. The simulation of segmentation and no segmentation.

To compare size-based burst assembly scheme and conventional burst assembly scheme, in which the size of low-class is not limited, we evaluate the performance by changing the ratio (maximum size of low-class burst / maximum size of high-class burst) changes from 0.2 to 0.8. If the ratio increases, the maximum size of low-class burst also increases. And, as shown in Figure. 40, the blocking rate increases when the maximum size of low-class burst increases. Because the opportunity of finding void interval increase when the size of low-class burst is small.

Figure. 41 compares the simulation results between the proposed scheme and the conventional burst assembly scheme when the ratio between maximum size of low-class burst and high-class burst is 0.5 in the situation of complete class isolation. As shown in the result, the proposed scheme, limiting the burst length of low-class, improves the blocking probability of low-class, while the blocking rate of high-class remains almost the same.

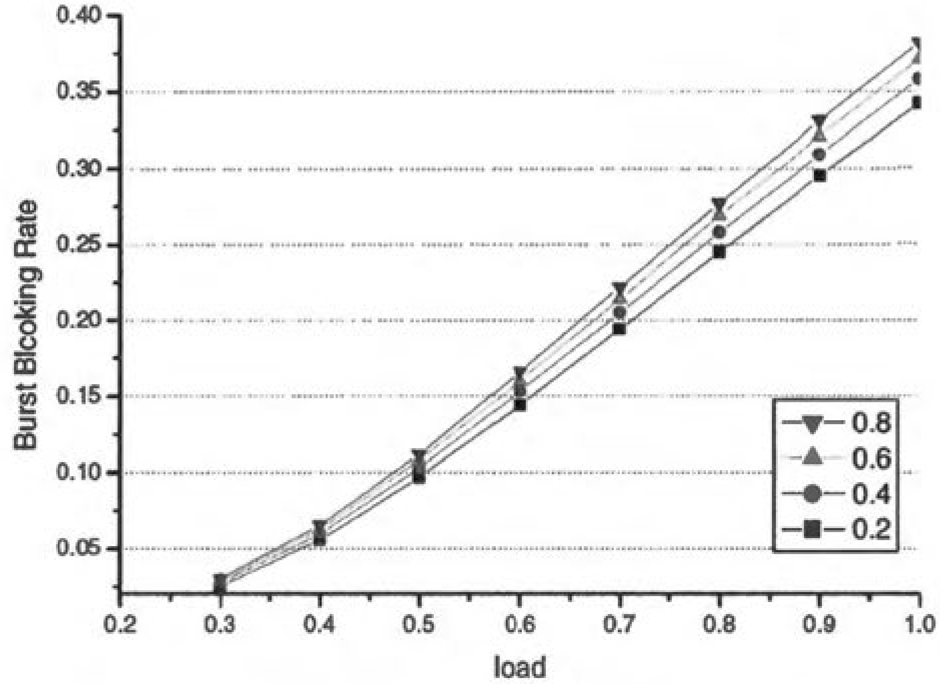


Figure 40. Relation between blocking rate of low-class burst and its length.

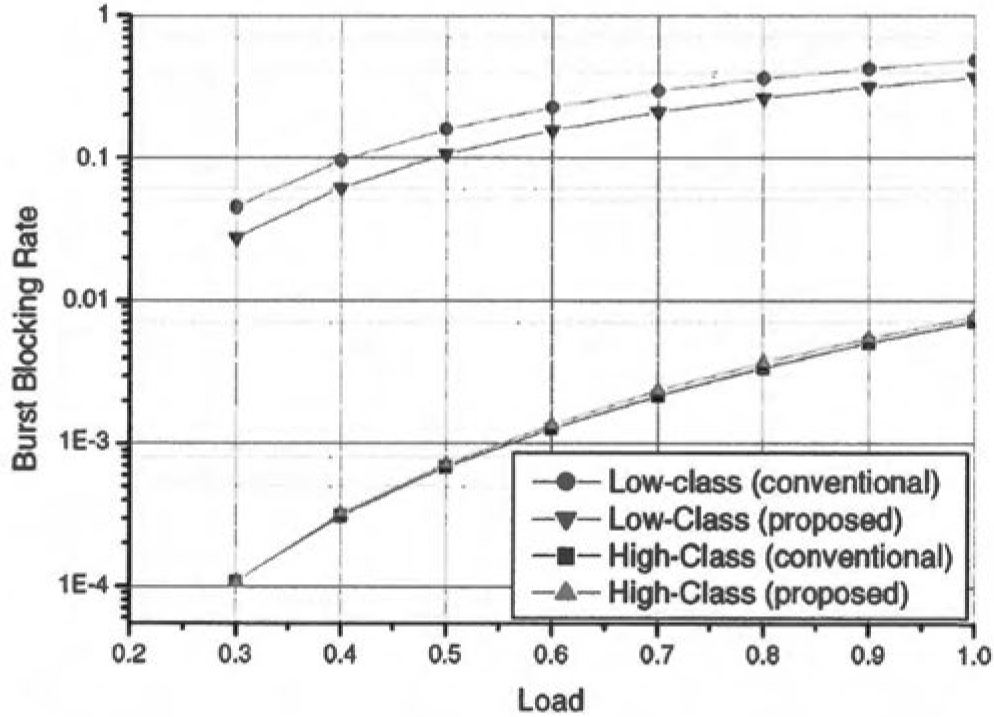


Figure 41. Conventional scheme and proposed burst size limiting scheme.

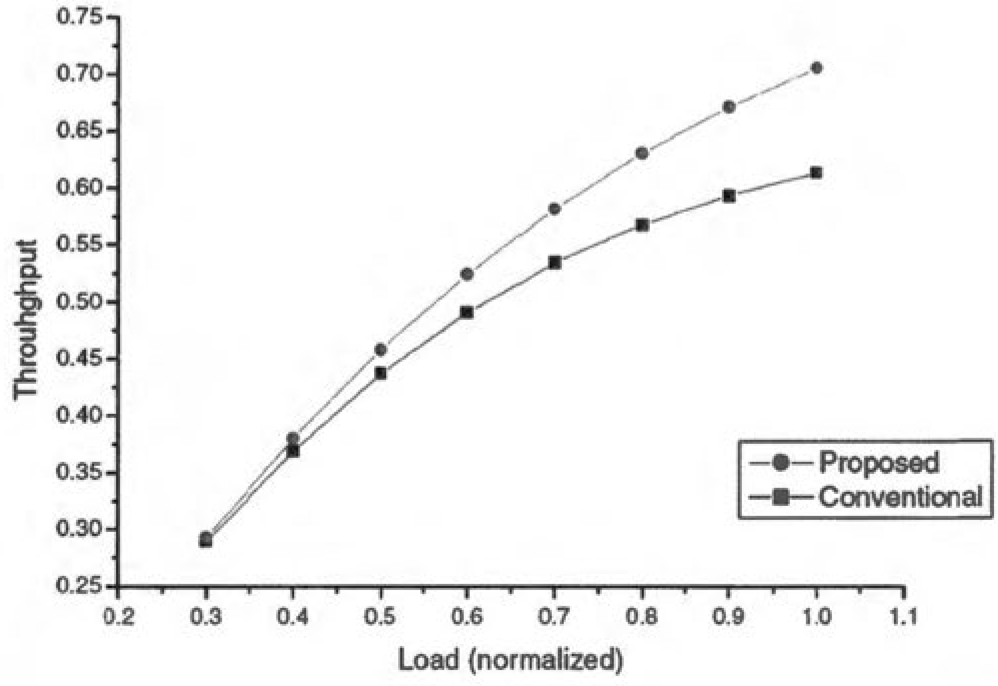


Figure 42. Throughput between conventional and proposed burst size limiting scheme.

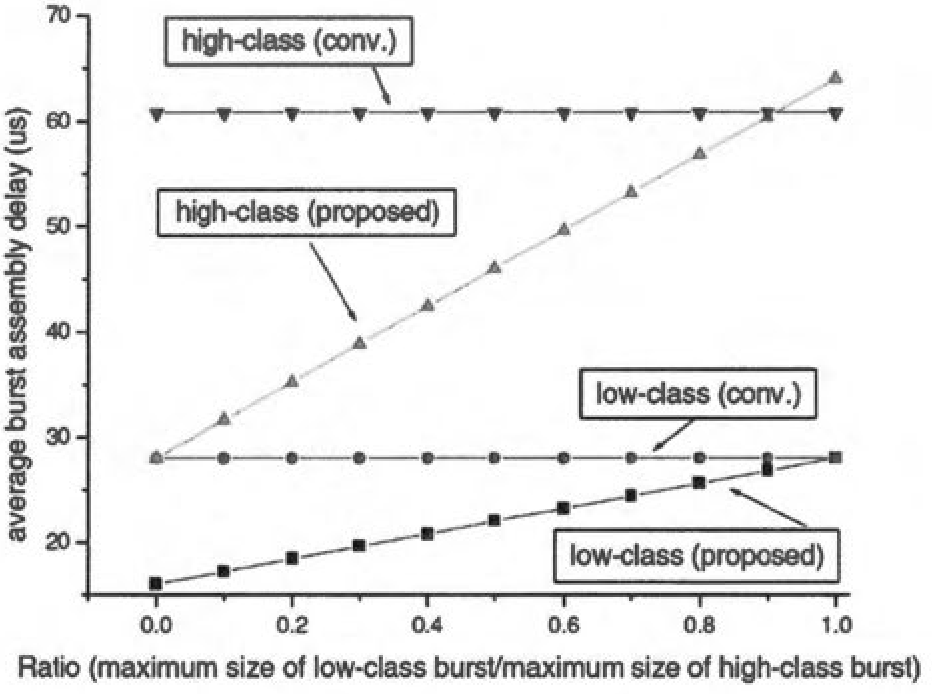


Figure 43. Burst assembly delay for low and high class bursts.

The throughput of the proposed scheme is improved (as shown in Figure. 42) because it provides greater opportunity to find more void intervals than the conventional scheme. The proposed scheme also shows gain in delay performance because extra offset time is reduced from the maximum length of bursts to the maximum length of low-class bursts. Figure. 43 shows the average burst assembly delay as the ratio changes from 0 (16 us) to 1 (40 us). As shown in the figure, the burst assembly delay is minimized when the value of the ratio is small. Though the assembly delay is small in this region, the number of low-class bursts increases dramatically and the traffic load for BCP increases. Therefore, there is a tradeoff between burst assembly delay and the offered load of control channel.

5.1.3 Analysis for Edge Core Node Combined

Blocking rate analysis is performed for the conventional scheduling algorithm and our proposed data channel scheduling algorithm. Three ingress node and one core node generate data bursts equivalently with Poisson distribution. We assume the data burst size from ingress nodes is same for simplicity. All links consist of 8 wavelengths.

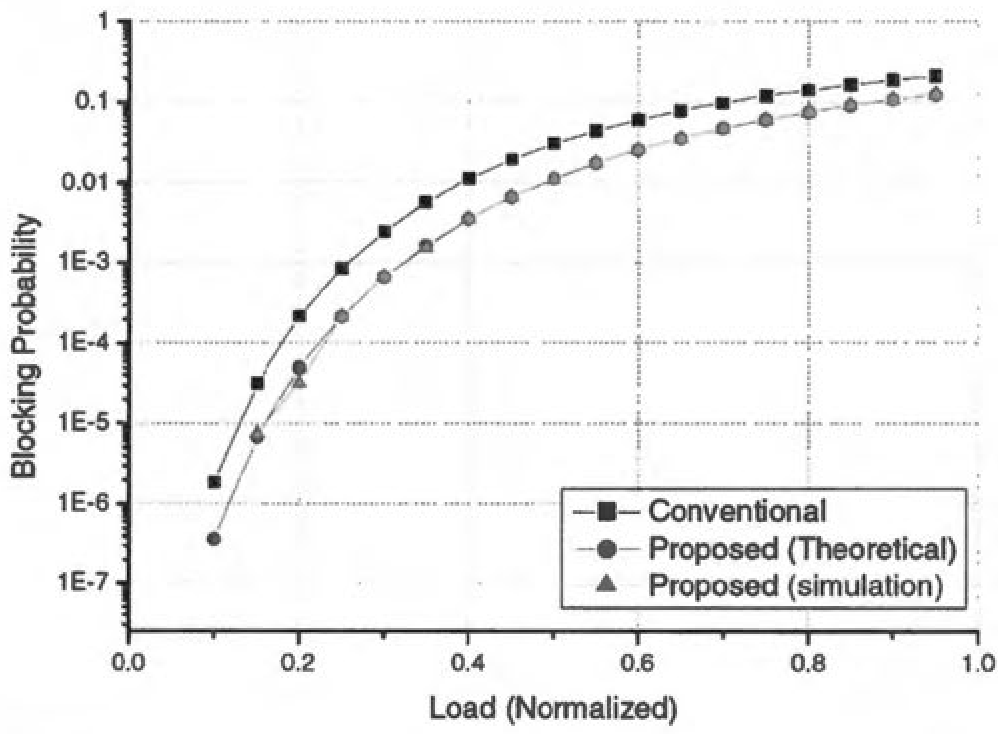


Figure 44. Blocking rate in conventional and proposed burst scheduling algorithm.

In figure. 44, the burst blocking rate comparisons between the conventional and our proposed data channel scheduling algorithm are presented for the edge/core combined OBS network. It is clearly shown that proposed algorithm has better performance than conventional algorithm because self-generated data bursts do not affect the overall burst blocking rate. Therefore, it is possible to save overall resources to be provided for guaranteeing a certain level of the blocking probability.

5.1.4 Analysis for Fairness Guaranteed Wavelength Grouping

The analysis results for wavelength group deduced by using the equation appeared in previous chapter are shown from figure. 45 to 47. The throughput of OHG bursts is shown in figure. 45 when the number of wavelength is 16. As shown in the figure. 45, the throughput of OHG bursts increases when the offset time ratio to the mean burst length of TDB increases. The number 0.2, 0.4, 0.8 and 1.0 in figure 5 means the offset time ratio the mean burst length of TDB. The reason why the throughput of OHG bursts does not increase with the traffic load of TDB is that the available void intervals for OHG bursts are decreased with increasing the load TDB. If the offset time ratio increases to 20, the throughput of OHG bursts approached one when the traffic load of TDB is low due to the sufficient void intervals. The analysis results do not appear because of space limitation.

Figure. 46 shows the total throughput of network when the offset time ratio to the length of TDB changes from 1 to 20. As shown in figure. 46, the total throughput approaches to 1 when the offset time increases. If the ratio is greater than 10, the throughput is almost saturated. The main portion of throughput improvement is due to the throughput improvement of OHG bursts. Figure. 47 shows the total throughput when the numbers of wavelength are 1, 2 4, 8 and 16 when the offered load of TDB is 0.5. Analysis results shows that the throughput is saturated when the number of channel is larger than 8. This means that the main factor of the throughput improvement is ratio of the offset time to the transit bursts not the number of wavelength in wavelength group.

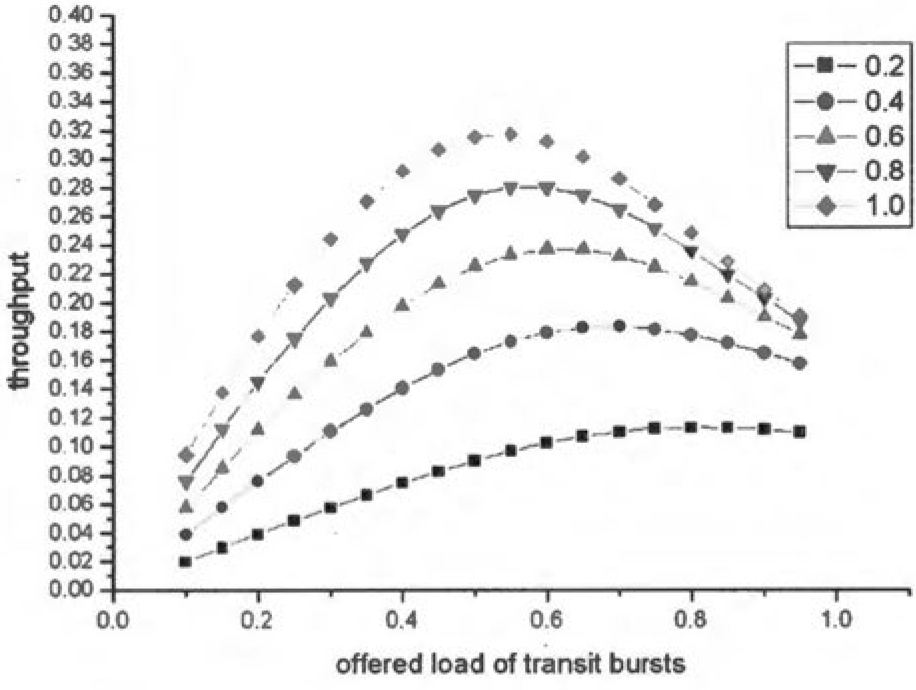


Figure 45. Throughput for the OHG bursts.

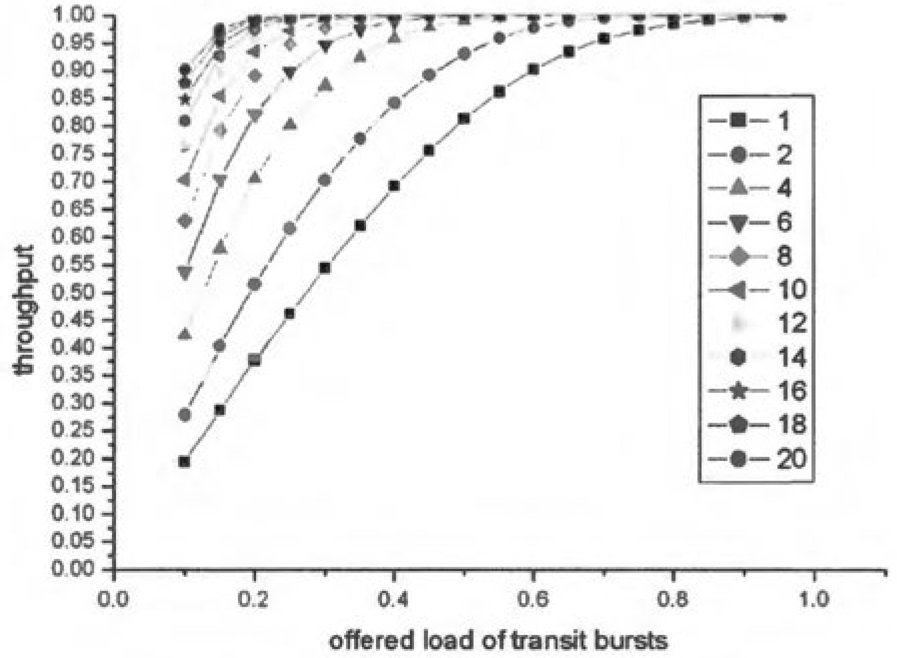


Figure 46. Throughput of the wavelength number.

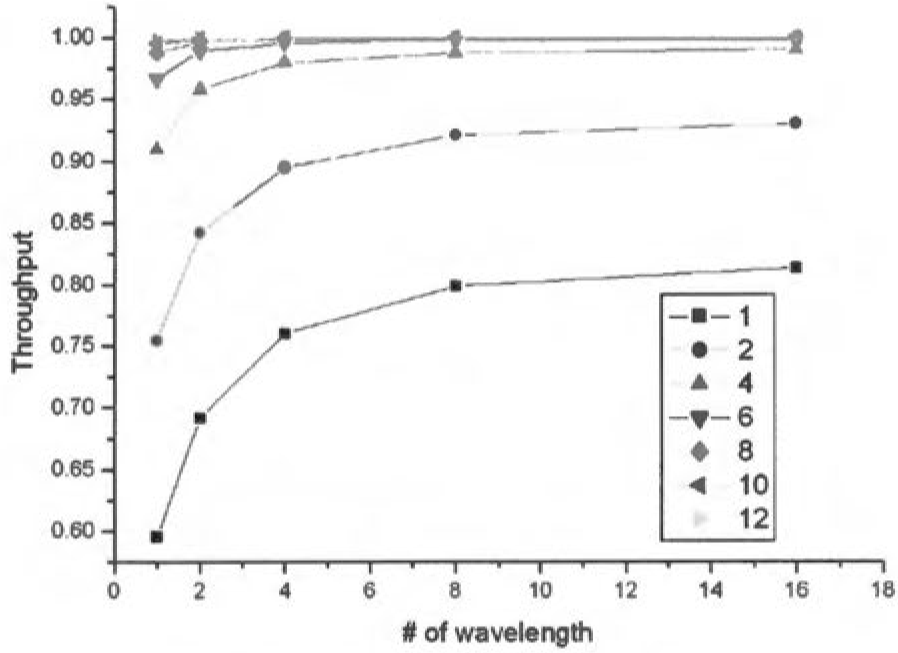


Figure 47. Throughput of the wavelength.

5.1.5 Analysis for Piggy Backing

In this section, the theoretically analysed blocking rates for the low and high class burst follow. Before presenting the results of piggy backing, the results of priority model are presented through Fig. 48 to Fig. 51 when the number of wavelength is 8. To investigate the effect of the traffic ratio between high and low class burst, the ratio has changed and got the results. In Fig. 48, the traffic of the high class is very small, 5% of the total traffic. In this case, the blocking rate for the high class is very low. This is because only small volume of high class traffic compete to occupy network link and low class bursts do not influence the blocking rate of the high class bursts. The advantage of the high class is achieved by the sacrifice of the low class burst. For low class burst, the blocking rate is a bit higher than that of class-less bursts. As the traffic volume of the high class burst increase, the gap of the blocking rates between high class and low class become narrow as shown in the following figures. This is the results of the increased blocking rate for high class bursts. For the low class burst, the blocking rates tend to decrease while that of high class bursts is likely to increase.

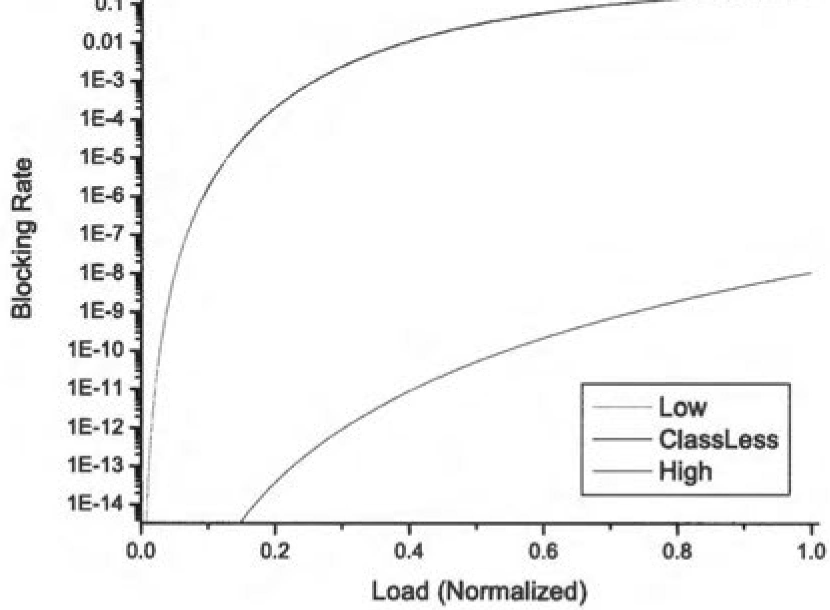


Figure 48. Priority Scheme; traffic ratio (H = 0.005) : (L= 0.95).

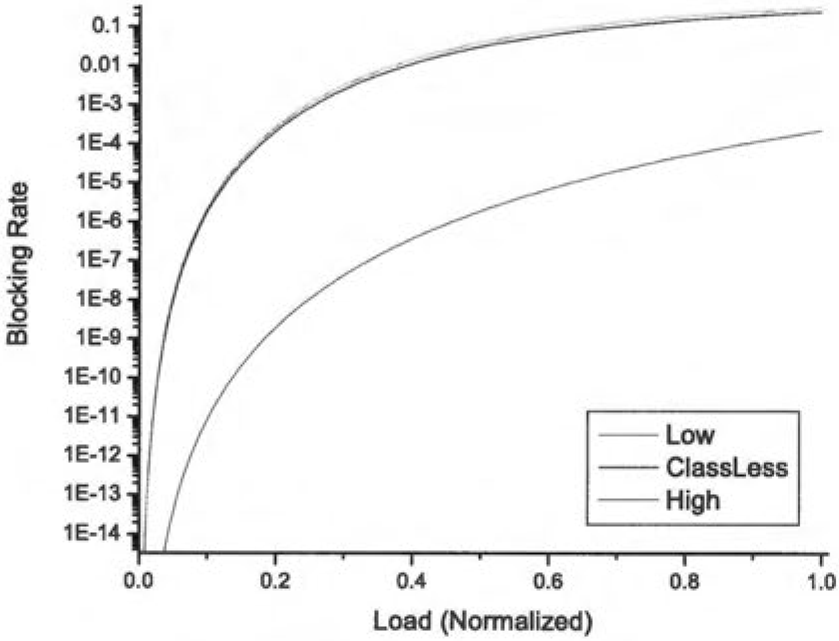


Figure 49. Priority Scheme; traffic ratio (H = 0.2) : (L= 0.8).

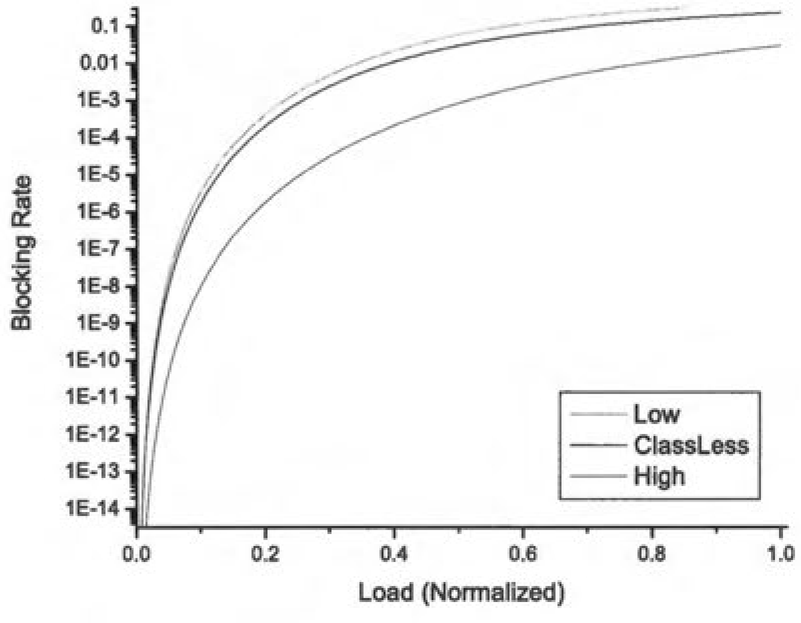


Figure 50. Priority Scheme; traffic ratio (H = 0.5) : (L= 0.5).

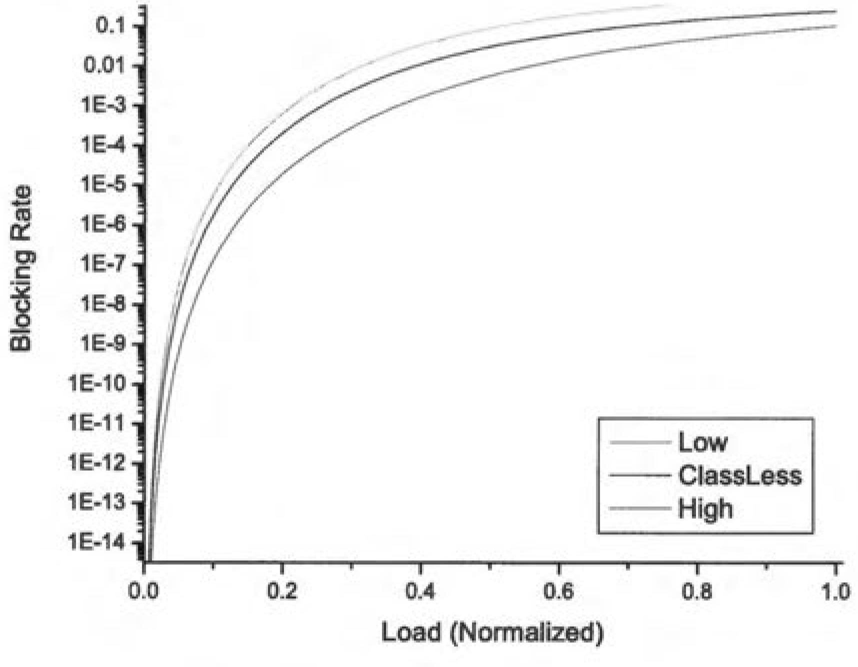


Figure 51. Priority Scheme; traffic ratio (H = 0.7) : (L= 0.3).

The analysis results of piggy back model are presented through Fig. 52 to Fig. 55 when the number of wavelength is 8. To investigate the effect of the traffic ratio between high and low class burst, the ratio has changed and got the results. In Fig. 52, the traffic of the high class is very small, 5% of the total traffic. Compared to the priority model for the high class burst, there is significant decrease of the blocking rates in the piggy backing model while those of the low class burst have very little difference. This piggy back scheme provides lots of benefits for the high class bursts while scarifying the performance of the low class bursts.

The following analysis results show that the differences between low class and high class goes to be narrow. This is because the blocking rates of high class burst become higher due to the traffic volume increase in the limited wavelength. Therefore, this piggy back model has a benefit when the traffic volume of the high class bursts is small. In this environment, the piggy backing model can be used in the commercial OBS networks.

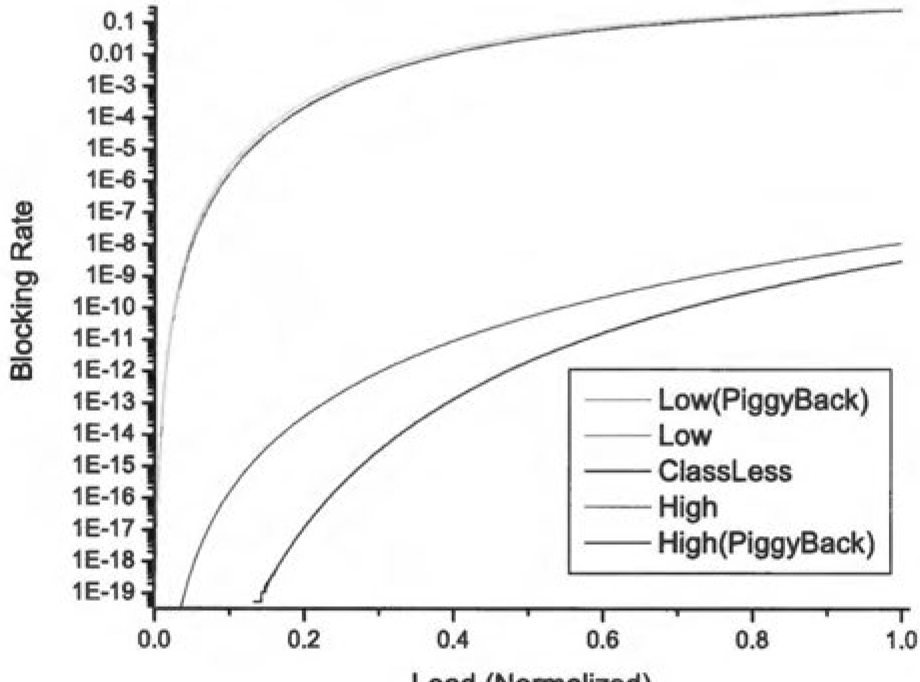


Figure 52. Piggy backing; traffic ratio (H = 0.05) : (L= 0.95).

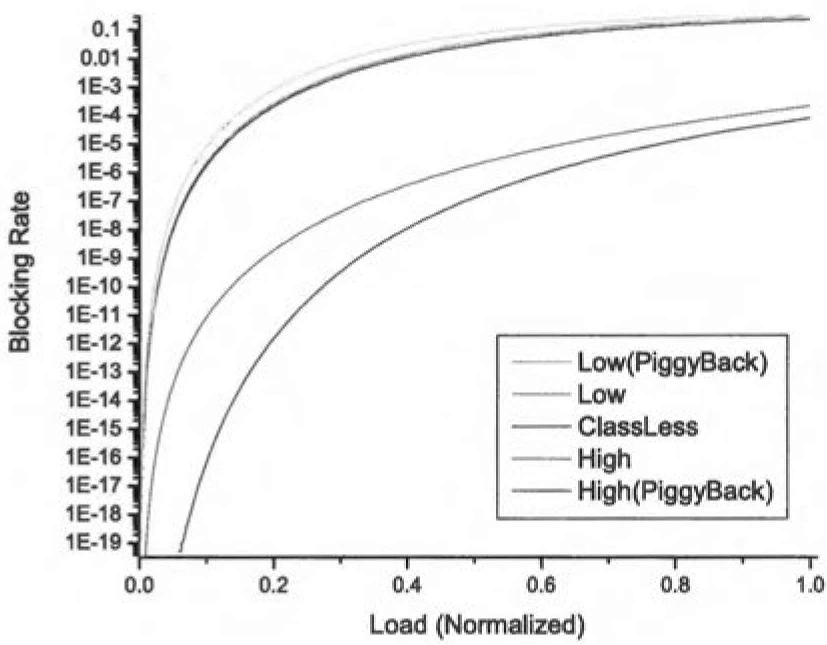


Figure 53. Piggy backing; traffic ratio (H = 0.2) : (L= 0.8).

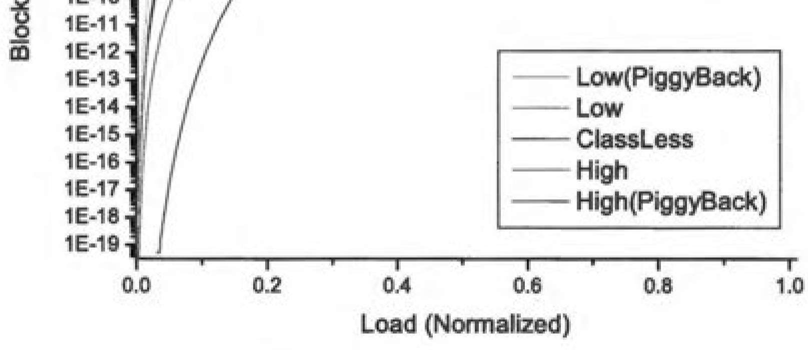


Figure 54. Piggy backing; traffic ratio (H = 0.5) : (L= 0.5).

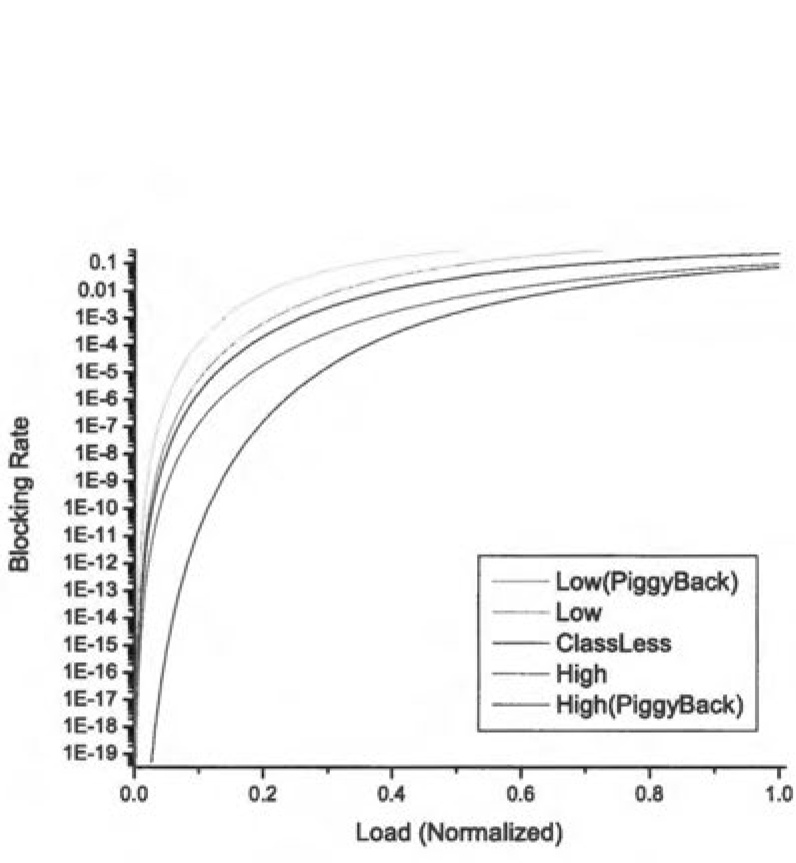


Figure 55. Piggy backing; traffic ratio (H = 0.7) : (L= 0.3).

5.2 Analysis of OBS Metro Ring Networks

5.2.1 Look Ahead Optical Burst Transmission

In this section, we make a simulation and compare the results with the mathematical results. As shown in Fig. 56, the delay of the simulation is little higher than the analysis results. The reason of the delay increase is that the wavelengths are not ideally separated as shown in figure. 53, so GBs should skip the current void when void size is not larger than burst's length. Thus, even though the small discrepancy between analysis and simulation exists, we conclude that the equation is valid for LAOBT delay calculation.

Next, our scheme is compared with the previous work (BRR STDM [3]) by using the simulation environments as shown in Table 4. The WDM metro ring network is considered as the simulation topology in which the number of nodes is four and the incoming traffic from access networks is assumed to be evenly distributed to each node. In the BRR STDM, a signaling channel is added to the four data channels, but in LAOBT only four data channels are used.

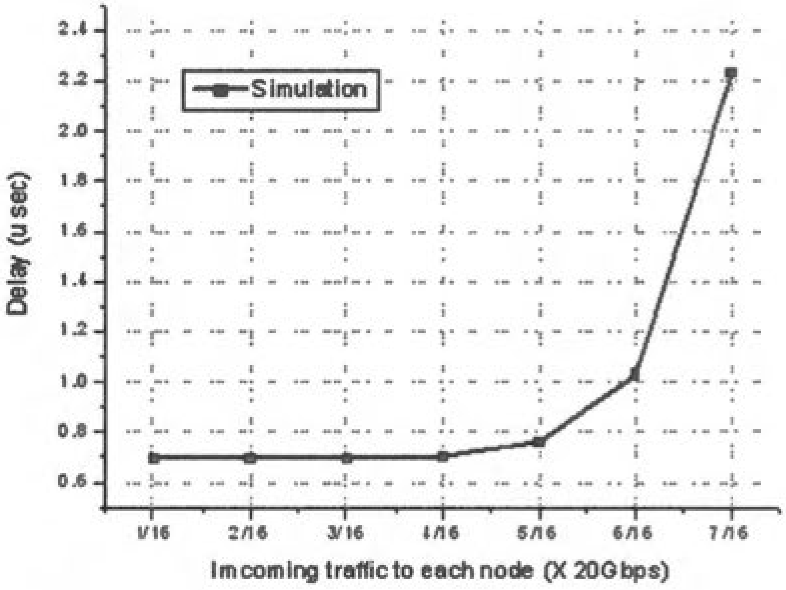


Figure 56. Comparison between analysis and simulation.

The incoming traffic from access networks at each WDM node ranges from 0.01Gbps to 19.5Gbps. We assume that the link capacity (40 Gbps) of the WDM ring is fully utilized by the merged traffic from the access networks and previous nodes when the incoming traffic reaches 20Gbps. As a traffic model [8] , we choose self-similar traffic rather than Poisson traffic because, when the range of the shape parameter (*F*) is $1 < F < 2.0$, the traffic behaves like Ethernet traffic. Due to the page limit, we present simulation results when *F* is 1.6 but the results are quite similar for other values of the shape parameter.

The simulation results in figure. 57 and figure 58 illustrate aforementioned properties. At low input traffic load, the delay of the LAOBT is slightly greater than that of the BRR STDM because the FDL size of the LAOBT is longer than that of the BRR STDM. The LAOBT, however, has smaller queuing delay at high input traffic load as shown in figure. 54 (b). Also, we observed that delay increment of LAOBT is less affected by input traffic especially in heavy traffic load compared to that of BRR STDM.

This delay enhancement stems from the insertion-based burst generation scheduling described in Section 2. Consequently, the delay increment due to the larger FDL is compensated by using the appropriate scheduling scheme at the TX queue.

Table 4. Simulation environment.

MAC protocol	BRR (STDM)	LAOBT
Number of nodes (N)	4	
Link capacity (R) per wavelength	10 Gbps	
Light velocity in the fiber	$2 \cdot 10^8$ m/sec	
Ring length	80 Km	
Packet size	75 ~ 1526 Byte	
Overhead	52 nsec	
Traffic type	Self-similar (F=1.6)	
Offered load	0.01 ~ 19.5 Gbps	
FDL length	16 m	2.44 Km
Number of wavelength(W)	5 (C:1, D:4)	4
Queue selection	None	Longest queue selection
Channel selection	None	Max void first

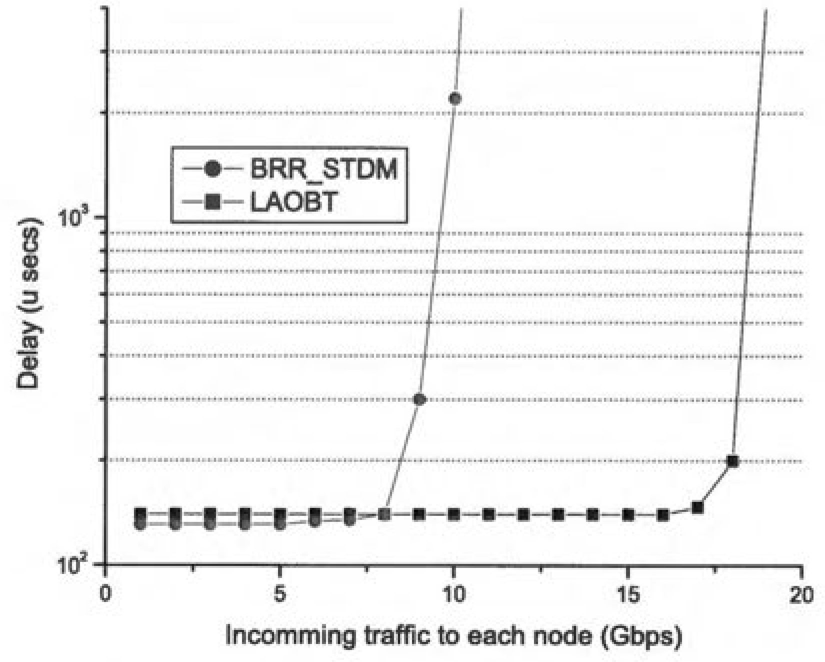


Figure 57. Performance comparison between LAOBT and BRR STDM (delay).

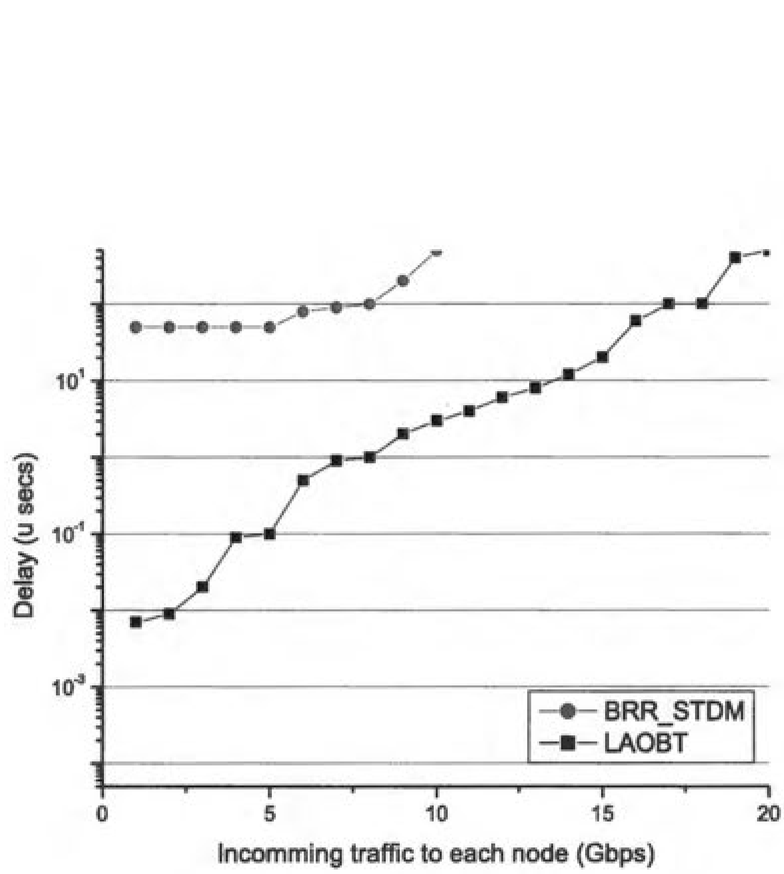


Figure 58. Performance comparison between LAOBT and BRR (delay in Queue).

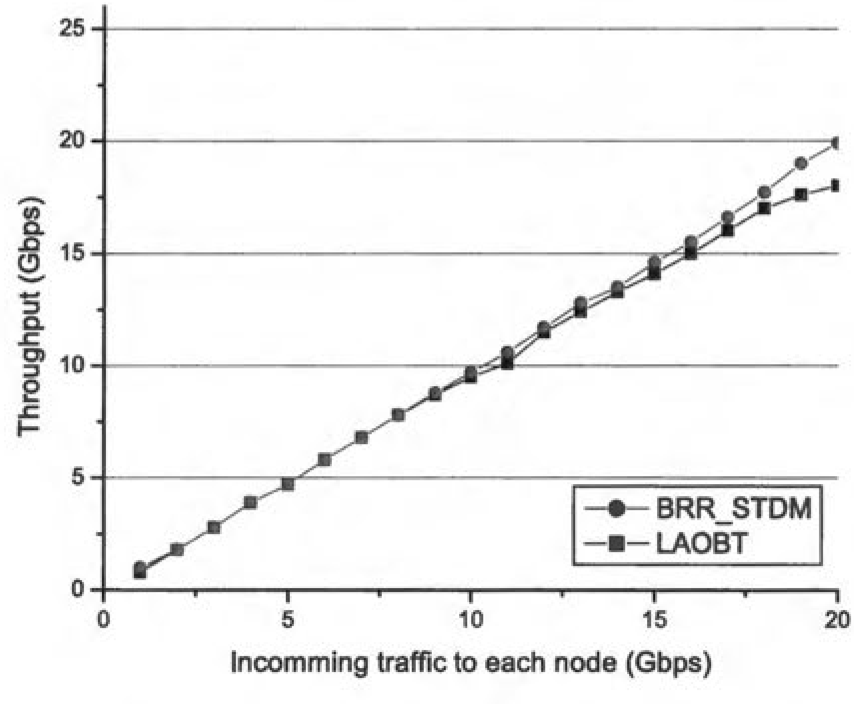


Figure 59. Performance comparison between LAOBT and BRR STDM (throughput).

In the BRR STDM, due to its position-based priority scheme [3], half of the link capacity is not used at the high input traffic load situation because this scheme gives higher priority to the previous nodes than the current node and limits the bandwidth allocation ratio for each node. On other hand, the voids of TBs in LAOBT can be completely filled by GBs so there are no gaps between bursts. Figure. 59 shows the relation between the offered traffic and the throughput at a link. We observe that the throughput of the LAOBT is always higher than that of BRR STDM.

5.2.2 Traffic Adaptive Burst Assembly

To verify the ideas of burst generation scheme with adaptive traffic loas, we have implemented the LLB concept in a DWDM ring network by using C++ programming language in a Linux environment. The parameters used in this system are illustrated in Table 5. The variation of timeout value is shown in Fig. 60, which is in agreement to equation (6.3). Its value is rapidly reduced when the traffic load increases. This change determines the number of data unit in the LLB burst as shown in figure. 61. The number of data unit in a burst is more than 10 regardless of the traffic load. Therefore, the major property of optical burst switching is validated in the proposed scheme.

Table 5. Simulation parameters for LAOBT

Number of Nodes	4
Link Capacity per Wavelength	10 G bps
Ligh Propagation Speed in Fiber	2 x 108m/sec
Ring Length	80 Km
Data Unit	75 1526 Byte (evenly distributed)
Traffic Ttype	Poisson (Exponentially Distributed)
Overhead	52 nsec
FDL Length	2.44 Km
Number of Wavelength	4
Queue Selection Scheme	Longest Queue Selection
Channel Selection	Max Void First

On the other hand, there is a trade off in terms of the delay as shown in Fig. 62. While the delay at the transmission queue at the IVF is less than 10 μs in the light load, that of proposed scheme is more than that of IVF. However, it is not a problem in optical networks because 200 μs delay in the transmission queue has a minimum effect on the end to end (E2E) delay criteria. What is more, even though there is the light load starvation when the volume of traffic is low because of the long timeout value, this can be improved by adjusting the timeout values.

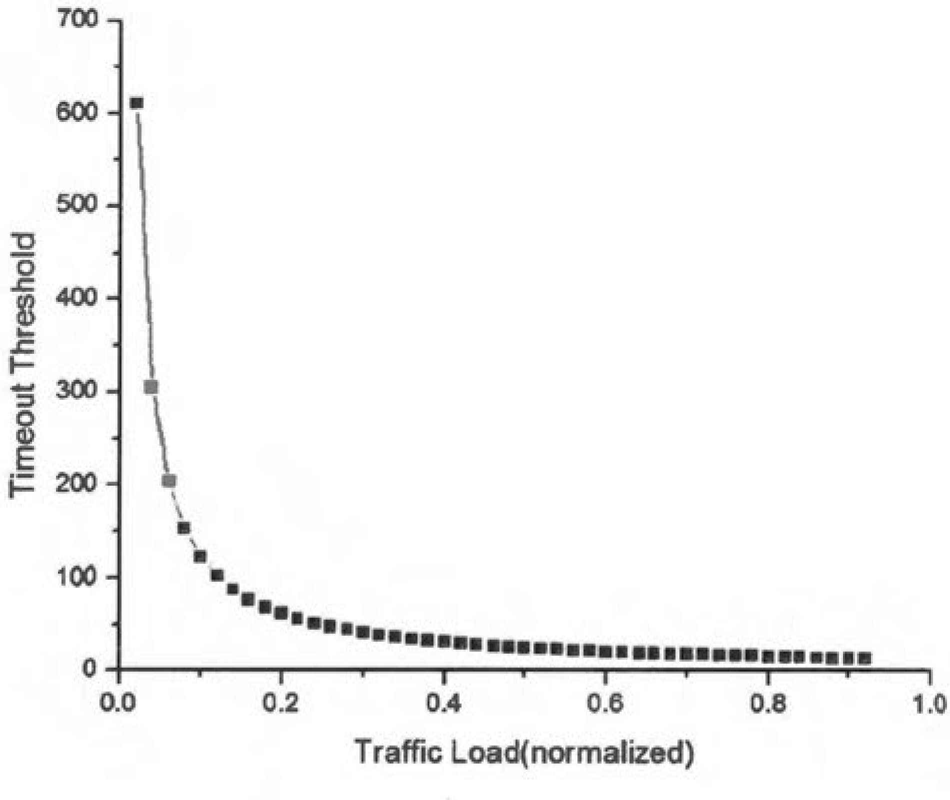


Figure 60. Time out VS. traffic load.

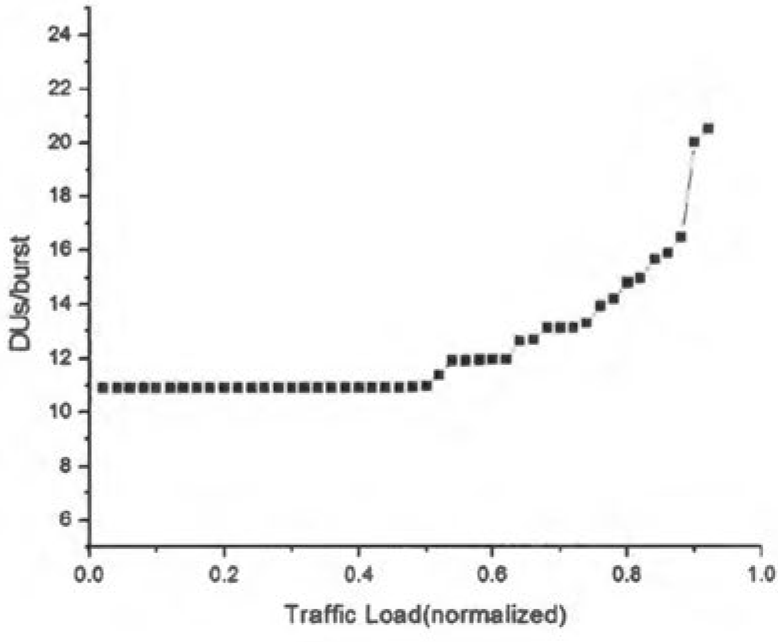


Figure 61. LLB packing efficiency.

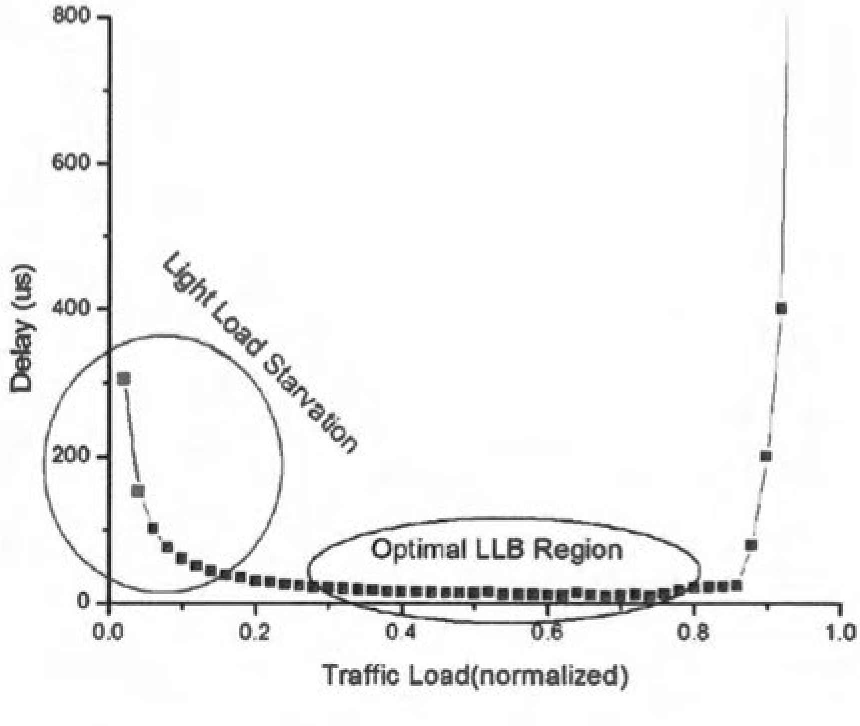


Figure 62. Queuing delay VS. traffic load.

5.3 Conclusion

In this chapter, we interpreted and verify the mathematical analysis by comparing those of simulation results. The Poisson traffic model was used to compare the results of simulation and theory because self similar traffic can't be compared with mathematical results due to the characteristics of the traffic pattern. The interpretation results show that the mathematical analysis is well matched to the simulation results within allowed margin. Except for several cases which can not be analyzed mathematically, the mathematical analysis were verified by performing computer simulation. The comparision results is minimal in research standard.

First of all, we compared the results of mesh networks. In this analysis we performed the simulation to compare the results of edge core combined node. The verification results show that the proposed scheme has an advantage in terms of the blocking rate. Also we verify that the conservation law can not be used in completely isolated class. This is verified with simulation and the illustration. For the blocking reduction scheme, we analyze the segmentation scheme and piggy backing scheme. The analysis results of the segmentation shows that the segmentation scheme is outperformed to the conventional scheme. For the piggy backing scheme, the mathematical results is well matched when we verify in our test bench.

Secondly, we verify the network performance in the loss less metro ring networks. The mathematical results for the delay and network throughput are compared to those of the simulation results. Immediate void filing scheme is better in terms of the delay performance, it is vulnerable to sustain burstness property. The lately proposed traffic adaptive burst generation scheme can meet the intrinsic property of the optical burst switching.

6 Thesis Conclusion and Recommendations

6.1 Summary of Thesis

In this dissertation, we prove that previously studied conservation law does not apply to the completely isolated classes. We drive the different performance analysis method for low class bursts. Also, we change the analysis facet from edge/core node separated studies to edge core combined node. In this environment, we drive analysis method and suggest performance improvement scheme. To implement loss less burst transmission, the LAOBT scheme is proposed. With this scheme the delay and link utilization increase. To sustain burst property, we also proposed traffic adaptive burst generation scheme.

All the mentioned transmission schemes are based on the insertion scheme. To insert efficiently and concise, the offset time is to be fixed. With constant offset time, the arrival time of next nodes is easily estimated. So the available residue bandwidth increase. The analysis and simulation results show that our proposed schemes have a good network performance.

In this chapter 2, we introduced the new concept in the optical switching research area. Due to the property of the hybrid circuit and packet switching, optical burst switching technology has received lot of attention. However, while it has lots of benefits, there are some limit to overcome to be deployed in commercial networks. With property of ackless resource reservation scheme, OBS is vulnerable to the blocking rate. Fairness among the same class burst is another issue to be address. This fairness violation happen when the number of remaining destination is different among burst in offset time based QoS priority scheme. Early arrival is the other issue to be solved. If the data burst arrived before the control packet, the data burst would be dropped because the node do not ready to deal with because it does not have any information regarding routing.

To address these problem, several schemes have been considered among researchers. First of all, to compensate the high blocking probability, deflection routing, burst cloning, resource overprovisioning, and burst segmentation have been considered in mesh networks. Bursts are rerouted to an alternative link when the designated path for the bursts is preempted for another burst in deflection routing scheme [31]. In burst cloning scheme, the bursts are copied and sent twice to the destination [16]. In addition, the packets which are located in the overlapped area in a bursts between contending bursts, are lost only when bursts contend for the same link while the packets in non-overlap area do not drop. This scheme avoids full packet loss in bursts and decreases the packet blocking rate. Resource overprovisioning scheme means that networks are designed to deploy more network resources than needed to reduce burst blocking rate.

In this chapter 3, we designed the optical nodes for mesh networks and metro ring networks. For the mesh networks, we change the concept of the burst generation. Instead separating core nodes with edge nodes in optical transmission network, the core edge node combined networks is introduced. These nodes have both function of generating bursts and switching bursts. In this network structure, the blocking rate will be decreased compared to the conventional edge core node separated scheme.

We also changed the node architecture to avoid fairness problem in the offset time based QoS priority scheme. By using the concept of the wavelength grouping, the same class bursts are grouped according to the number of remaining node. When every bursts arrive, the wavelength converter change the bursts in terms of the remaining hops to the destination. By grouping bursts, the fairness violation can be avoided.

To implement loss less burst transmission, we drive the insertion based burst generation scheme. By utilizing the void between transit bursts, the generated bursts at the current nodes can be transmitted without collision with the incoming bursts. In designed node, we split the optical signal by using the optical split and fiber delay line to predict the size of the voids between arriving bursts.

To reduce the delay in the Queue, we consider using the immediate burst generation scheme. We drive lots of the burst generation and scheduling scheme to managing wavelength efficiently. This scheme has an advantage of decreasing the waiting time in the transmission queue. Even though this scheme is good at reducing queuing delay, it has a disadvantage of losing the property of the burstness.

In this chapter 4, we performed the analysis of the network we proposed in mesh network and metro ring networks. Several assumption and network models are presented to analyze the network performance mathematically.

First of all, we drive the equation for the blocking probability in mesh network in the priority class scheme by using the Erlang-B formula. The comparison between completely isolated class and segmentation is also presented. The performance of the segmentation scheme is analyzed mathematically and show that segmentation scheme is better than that of conventional scheme.

One of the blocking reduction scheme, we introduce the scheme of piggybacking and analyze the blocking rate for the priority class by modifying the Erlang-B to our network model. For the throughput in fairness guaranteed network, the throughput of the network is driven successfully.

For the delay analysis in the lossless metro ring network, we can drive the mathematical formula by introducing the virtual queuing system. By using this assumption, the delay in the queue and the throughput is calculated. To calculate the void size in the look ahead burst transmission system, we analyze the relationship between the arriving burst and the fiber delay line. We can predict the maximum burst size generated in the current node.

To sustain the burstness property in look ahead burst transmission scheme, we introduce the traffic adaptive burst generation scheme. This scheme is useful in terms of maintaining the number of packets in a burst regardless of the traffic load. We determined the size of the burst by considering network volume and drive the equation for the burst size.

In this chapter 5, we interpreted and verify the mathematical analysis by comparing those of simulation results. The interpretation results show that the mathematical analysis is well matched to the simulation results within allowed margin.

6.2 Novelty of the Thesis

This thesis has a novelty in terms of designing for optical burst switching network and analyzing network performance mathematically. In this thesis, the scheme of blocking reduction technology is drawn in both mesh networks and metro ring network. By inventing insertion based burst generation scheme, the blocking rate decrease as well as the throughput. We also make metro ring network loss free burst transmission system. To verify our system we compared our scheme with previously researched scheme. It proved that our scheme outperformed in term of blocking probability and throughput. We also make a theoretical analysis model and verify it with simulation results. The verification results show that the two results are almost same in the allowed range.

First of all, we compared the results of mesh networks. In this analysis we performed the simulation to compare the results of edge core combined node. The verification results show that the proposed scheme has an advantage in terms of the blocking rate. Also we verify that the conservation law can not be used in completely isolated class. This is verified with simulation and the illustration. For the blocking reduction scheme, we analyze the segmentation scheme and piggy backing scheme. The analysis results of the segmentation shows that the segmentation scheme is outperformed to the conventional scheme. For the piggy backing scheme, the mathematical results is well matched when we verify them in our test bench.

Secondly, we verify the network performance in the loss less metro ring networks. The mathematical results for the delay and network throughput are compared to those of the simulation results. Immediate void filing scheme is better in terms of the delay performance, it is vulnerable to sustain burstness property. The lately proposed traffic adaptive burst generation scheme can meet the intrinsic property of the optical burst switching.

6.3 Future Study

As an interim solution for optical packet switching, Optical Burst Switching (OBS) is considered as an alternative solution for optical Internet backbone. In the near future, with the help of the breakthrough technology, the OPS will be implementable technology. The OPS will be studied in the future if the optical buffers are invented in the material engineering.

Besides, to analyse the end to end delay in the optical networks, the performance analysis of the TCP is inevitable. The relationship between burst size and the contention widow need to be considered in the future study.

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Appendix A: List of C++ Program for the Dissertation

A.1 Erlang.c

To obtain the Erlang results, due to the computing power, the number of wavelength is limited.

Imput:

Traffic load

Number of wave length

Output

Blocking rate

A.2 Burst_assem.c

Simulate the traffic adaptive burst assembly scheme in the metro ring networks.

Imput:

Traffic (self-similar or poisson)

Output

Queuing delay and network throughput

A.3 Que_sel.c

Select the best queue among the transmission queue. Normally the maximum size queue is selected while in some case the queue having oldest packet is selected

Imput:

Transmission queue information such as number of packet in each queue and size of the queue and the packet arriving time

Output

Selected Queue index

A.4 channel_sel.c

Select the optimal wavelength to insert generated burst between arriving bursts.

Imput:

Information of the arriving burst such as void size and burst size

Output

Selected channel index

A.5 Sort_f.c

Sort the size of packet or burst

Imput:

Burst information

Output

Index of the longest one

A.6 priority.c

Get a result for the priority queuing scheme

Imput:

Network traffic

Output

Blocking rate for each classes

A.7. piggy_back.c

Get a result for the piggy backing scheme

Imput:

Network traffic

Output

Blocking rate for each classes

A.8. comp_exp.c

Generate complementary exponential traffic

Imput:

Traffic load

Mean burst / packet size

Mean inter arrival rate

Output

Poisson traffic (inter arrival time and size)

Appendix B: Research Proposal

TCP PERFORMANCE ANALYSIS BASED ON OPTICAL BURST SWITCHING NETWORKS

PROJECT PROPOSAL

SEOUNG YOUNG LEE

LXXSEO004

PREPARED FOR DR ALEXANDRU MURGU

DATE: JUNE 18, 2014

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Acronyms

ARQ	Automatic Repeat Request
BCP	Burst Control Packet
CoS	Class of Service
DB	Data Burst
DWDM	Dense Wavelength Division Multiplexing
EPS	Evolved Performance Scheme
FDL	Fibre Delay Line
FTTC	Fibre To The Curb
FTTH	Fibre To The Home
JET	Just Enough Time
LTE	Long Term Evolution
OADM	Optical Add and Drop Multiplexer
OBS	Optical Burst Switching
OCS	Optical Packet Switch
O/E/O	Optical Electrical Optical conversion
OLT	Optical Line Terminal
ONU	Optical Network Unit
OPS	Optical Packet Switching
OXC	Optical Cross Connect
QoS	Quality of Service
TAG	Tell And Go
TCP	Transmission Control Protocol
VOD	Video On Demand

CHAPTER 1: INTRODUCTION

1.1 Background

With the advent of high bandwidth consuming applications in wireless and wireless technologies, the demand of bandwidth in core networks has increased recently. In wireless area, advanced high speed radio interface technologies such as Long Term Evolution (LTE) and a lot of killer applications at smart phones operated with IOS and Android have generated amount of traffic. Additionally, users demand for multimedia applications such as YouTube, VOD, and video conference provoke the necessary of high speed information transmission in core networks.

There have been several researches to accommodate these high speed applications at core networks [1]-[5]. Optical technology has been considered as a reasonable solution because it has several benefits [6-10]. Optical transmission schemes such as Dense Wavelength Division Multiplexing (DWDM), Optical Add and Drop Multiplexing (OADM), and Synchronous Digital Hierarchy (SDH) have been used to provide high speed Internet services. Exchanging information at core network is another important area of consideration. To overcome legacy electrical switching technology, all optical switching technology such as Optical Cross Connect (OXC) has been thought of recently because this scheme does not need to optical to electrical (O/E) conversion and vice versa.

To improve current circuit based optical switching scheme, several technologies have studied in optical domains [9]. At optical circuit switching technology, due to limitation of optical buffer in optical domain, the wavelengths are assigned and switched by using wavelength converters at core nodes from source to destination when subscriber make contract with network service providers who own the optical transmission medium [11]. This optical circuit switching scheme would waste the bandwidth because links should be always connected regardless of the traffic existence. Recently, to achieve the statistical multiplexing gains in optical switching, optical packet switching (OPS) concept has introduced. Although OPS which can achieve higher utilization is attractive, there are practical limitations such as optical buffer and all optical processing. The only way of delaying optical signal is that of Fibre Delay Line (FDL).

As an interim solution for optical packet switching, Optical Burst Switching (OBS) are considered as an alternative solution for optical Internet backbone in the near future. OBS technology can cut through data messages without O/E/O conversion and guarantee the Class of Service (CoS) without any buffering. Under Just Enough Time (JET) [5], each optical burst is preceded by a BCP that contains information about the burst and the path that is to take through the network. By delaying the burst transmission by offset time, no additional buffering of the data burst is required while the burst control packet is electronically processed in each intermediate node in the path. At each node, the burst control packet attempts to reserve network resources to accommodate its burst. If sufficient resources cannot be secured at any node, the data burst is dropped when it arrives at that node. Even though OBS is considered as a strong candidate of next generation optical transmission scheme, it has some obstacles such as high blocking rate and burst assemble delay. The high blocking rate would influence the TCP performance such as size of the contention window.

1.2 Research Definition

As a contribution of the telecommunication industry, this research will focus on the TCP performance analysis based on the OBS transmission environment because TCP performance is closely related to that of applications. There have been studied to improve OBS throughput such as routing deflection, burst cloning, burst synchronization and burst segmentation. This research will study on the OBS throughput improvement scheme and perform analysis on the TCP throughput according to the OBS schemes.

1.3 Outline of the Proposal

This proposal is comprised of six chapters. Chapter 1 is a background of Optical networks and motivation of OBS. Chapter 2 gives an overview of the diverse OBS technologies. Chapter 3 presents the issues of the current OBS. Chapter 4 defines the problems, research topic and objectives. Chapter 5 gives the methodology of how the project will be achieved and the time line.

CHAPTER 2: OPTICAL SWICHING BACKGROUND

2.1 Properties of Optical Network

Optical technology is suitable for applications consuming large amount of bandwidth. There are several benefits of optical networks. Optical fibre is a proper solution for long distance communications because it does not need to amplify signals. While electrical signal in copper cable needs to be amplified almost every Kilo meters, optical signal can be transmitted up to several hundreds of Kilo meters without amplification. The emergence of DWDM technology is considered as a solution to accommodate the tremendously increasing demands of transmission bandwidth driven by the growth of IP-based data traffic. It is possible because fibre optics can deal with several wavelengths in a single fibre. Additionally, it is easy to implement protection and restoration in optical network. At optical ring structure, the recovery time is usually within 50 us by deflecting signal to the opposite direction.

The optical domain has been expanded to the home by using all optical IP networks, as shown in Fig. 1. As the demand of high speed Internet has increased. For some developed countries, the concept of Fibre To The Home (FTTH) is implemented after experiencing Fibre To The Curb (FTTC). In addition, at the nearby of the customer's facilities, Ethernet Passive Optical Networks (EPON) has been deployed by using the Optical Line Terminal (OLT) and Optical Network Unit (ONU) at network provider's side and user's side, respectively.

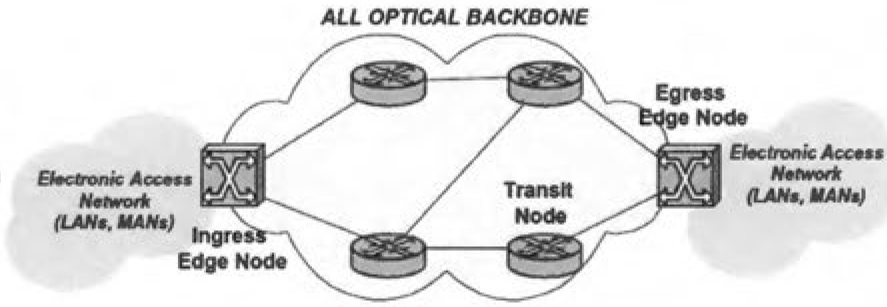


Figure 1 All Optical IP Networks [12]

2.2 Optical Circuit Switching (OCS)

The optical circuit Optical technology has considered as leased line service to satisfy business needs because it is reliable transmission technology. It usually provides long term connection to the subscribers by assigning and switching wavelengths at the core network almost permanently. Optical Add and Drop Multiplexer (OADM) is used to interface between user premises and those of network providers while wavelength switching is performed by using the wavelength converters and OXC. To transmit electrical signal in optical domain, E/O and O/E conversion devices are used.

Even though OCS guarantees the secure network services, it has drawback: bandwidth waste. Due to the intrinsic property of circuit switching, the connection should be maintained while there are no traffic on the network links. It results the waste of the network links. To enhance the network throughput, some alternative technologies are thought of.

2.3 Optical Packet Switching (OPS)

To obtain statistical multiplexing gain in optical networks, the idea of optical packet switching is introduced. In optical packet switching technology, similar to that of electrical domains, optical packets are switched in terms of packet by packet. So the throughput will dramatically increase due to the multiplexing gain property. To implement optical packet switching, the devices for buffering optical signal should be prepared. The only way to delay optical signal in optical domain is that of FDL at current technology status, which require several Kilo meters of fibre line to delay optical signal up to micro second. To process optical packet header, core router should delay optical signal by using FDL because optical signal processors at core router is not possible in current technology. Therefore, the alternative technology for OPS is considered.

2.4 Optical Burst Switching (OBS)

Although OPS technology which can achieve higher utilization is attractive, there are practical limitations such as optical buffer and all optical processing. Presently, optical burst switching (OBS) technology is under consideration as a solution for optical Internet backbone in the near future since OBS technology can cut through data messages without O/E/O conversion and guarantee the Class of Service (CoS) without any buffering.

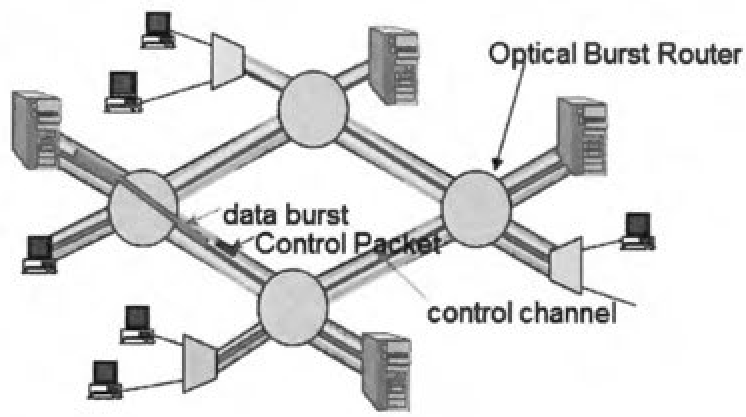
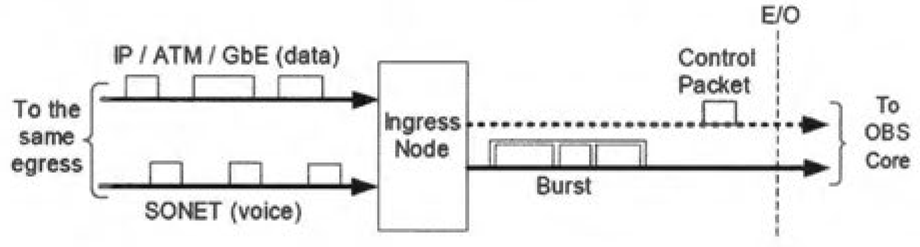


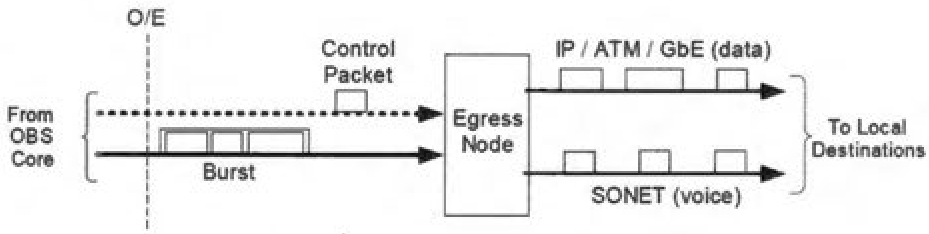
Figure 2 Optical Bust Switching Operation

Optical Burst Switching (OBS) is a new paradigm proposed to efficiently support growing broadband multimedia traffic either directly or indirectly over all optical WDM networks. OBS is based on one-way reservation protocols, such as Just-Enough-Time (JET) and Tell-And-Go (TAG) [1], in which a data burst (DB) follows a corresponding burst control packet (BCP) without waiting for an acknowledgement.

Under JET, each optical burst is preceded by a BCP that contains information about the burst and routing after assembling packets at the ingress nodes as shown in Fig. 3. By delaying the data burst transmission by offset time after transmitting BCP, no additional buffering of the data burst is required while the burst control packet is electronically processed in each intermediate node in the path as shown in Fig. 4. At each node, the burst control packet attempts to reserve network resources to accommodate its burst in Fig. 4. If sufficient resources cannot be secured at any node, the data burst is dropped when it arrives at that node.



(a) Burst Assembly



(b) Burst Disassembly

Figure 3 Burst Assembly/Disassembly at the Edge Node [14]

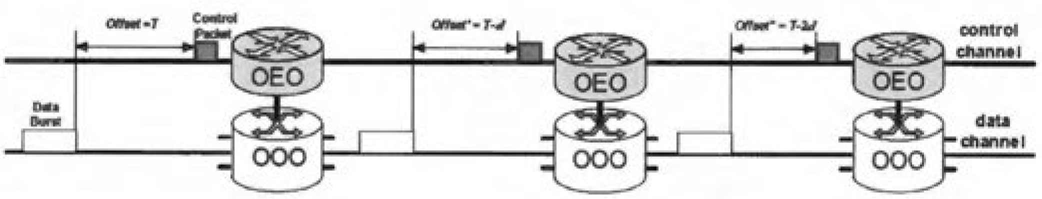


Figure 4 Separated Transmission of Data and Control Signal [14]

To provide QoS differentiation between high-class bursts and low-class bursts, JET uses different extra offset times for different class of bursts [2]. The basic idea of this scheme is to give a larger extra offset time to a high-class burst, thus enabling reservation for a high-class burst far in advance of low class burst and giving it a better chance to succeed. A long offset time enables a high-class burst to succeed in making a reservation. Studies have shown that the probability that a low-class burst will block a high-class burst can be negligible when the difference of offset time between these classes is a few times the average data burst length of the low-class [2].

CHAPTER 3: RESEARCH ISSUES IN OBS

3.1 Main Issues

Even though OBS has simple architecture, it has several weak points to be deployed at current core networks. Because of the original properties of Ack-less one way resource reservation, data bursts are vulnerable to blocking as well as the ingress node does not know whether bursts are transmitted properly or not. Unlike electrical switch, the bursts will lost when blocking happens because of the lack of optical buffer in optical domain. The reliable data transmission such as retransmission and ARQ is the role of higher layer.

Besides, there is a chance that data burst will arrive at egress node before BCP arrival: called Early Arrival. This problem is occurred when the offset time is not sufficiently large. As explained in Fig. 5., the offset time decrease as the bursts transverse nodes because the BCP has a O/E/O conversion and header processing at the core nodes. If summation time of spending at core node is larger than the calculated offset time, the burst cannot find proper output link because the nodes can not reserve network resources before the arrival of data bursts.

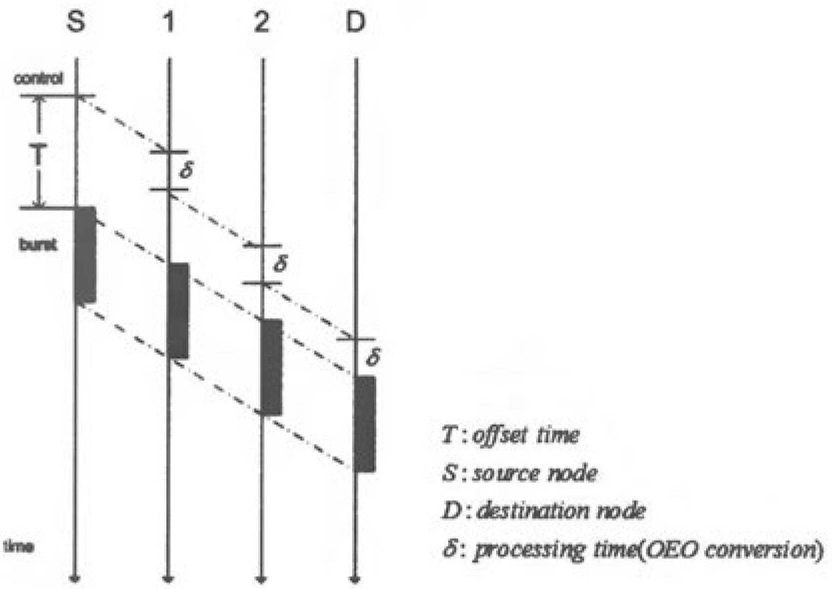
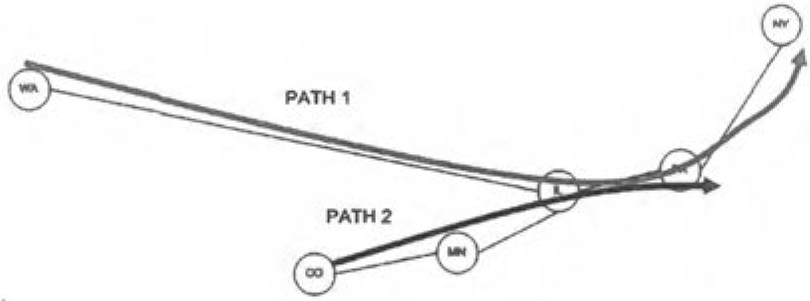
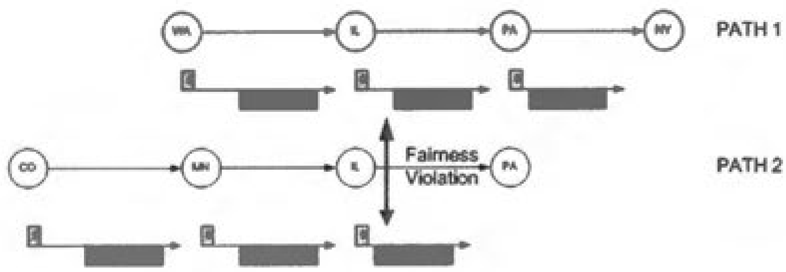


Figure 5 Offset Time Change

As mentioned, the QoS of bursts in OBS network is determined by offset time of the bursts [9]. But the offset time in mesh network would not be the same due to the different number of remaining hops at intermediate nodes as shown in Fig. 6. In Fig. 6, the offset time of path 1 is greater than path2 because the remaining number of hops for path1 is two while path2 is one. Therefore, the bursts in path1 have more priority than the paht2 at node IL. As we explained in this example, the fairness problems will be invoked among the bursts which have different routing path even though they have the same priority.



(a) Share same link.

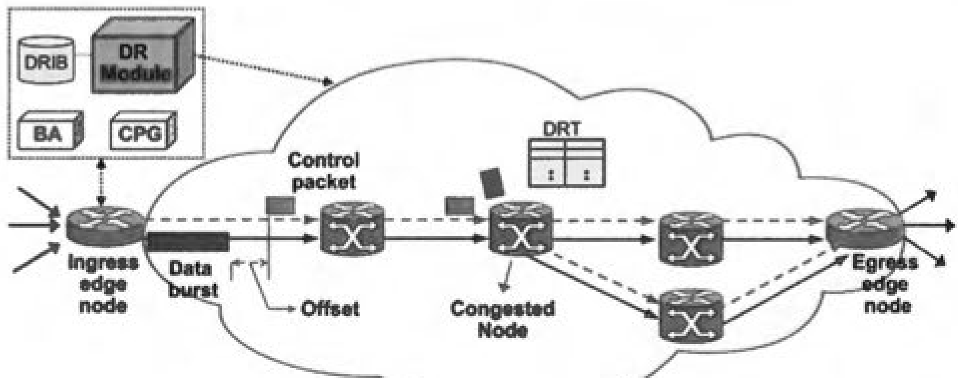


(b) Fairness violation at link between IL and PA.

Figure 6 Fairness Violation in Mesh Networks

Due to the Ackless resource reservation characteristics, OBS is vulnerable to the burst contention in core network. Unlike electrical router, optical switched cannot delay optical signal. This property leads to the information loss in optical domain. To reduce the burst loss, several schemes have studied: deflection, burst cloning.

Basic idea of burst deflection is that unused links can be utilized rather than dropping burst when congestion happens. As shown at Fig 7, when reserved link is not available, alternative link can be used for burst routing. This scheme improves the blocking rate while increasing complexity and traffic volume.



- BA: Burst Assembler
- CPG: Control Packet Generator
- DRT: DR Table
- DRIB: Deflection Routing Information Base

Figure 7 OBS Network with Deflection Routing [15]

One of the proactive schemes for reducing burst blocking rate is burst cloning. In this scheme, the bursts are replicated and sent duplicated copy of the burst through the network simultaneously. So, if the original burst is lost, the cloned burst may be able to survive. However, cloning bursts can invoke the traffic load to the networks.

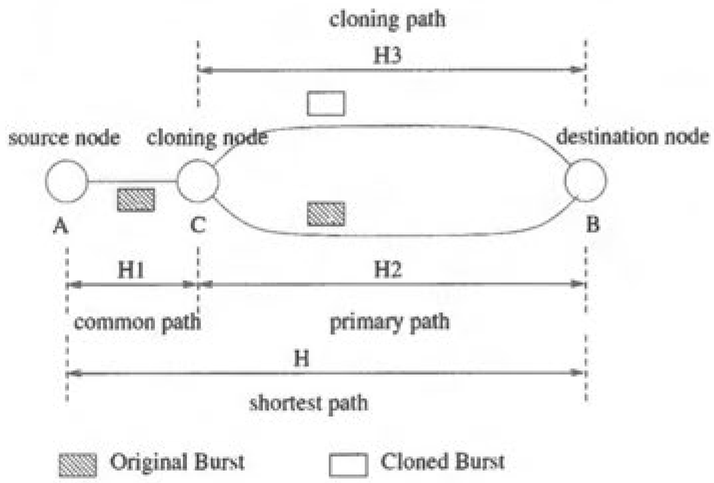


Figure 8 Burst Cloning [16]

3.2 Evolved Performance Scheme: Burst Scheduling

3.2.1 Burst Segmentation

Burst segmentation scheme is an effective contention resolution technique used to reduce the number of lost packets in the bursts when collision happens. To minimize the loss of information, only one of overlapped portion of burst between two bursts lost when contention occurs. As shown in Fig.9, the information loss rate decreases compared to that of non-segment scheme.

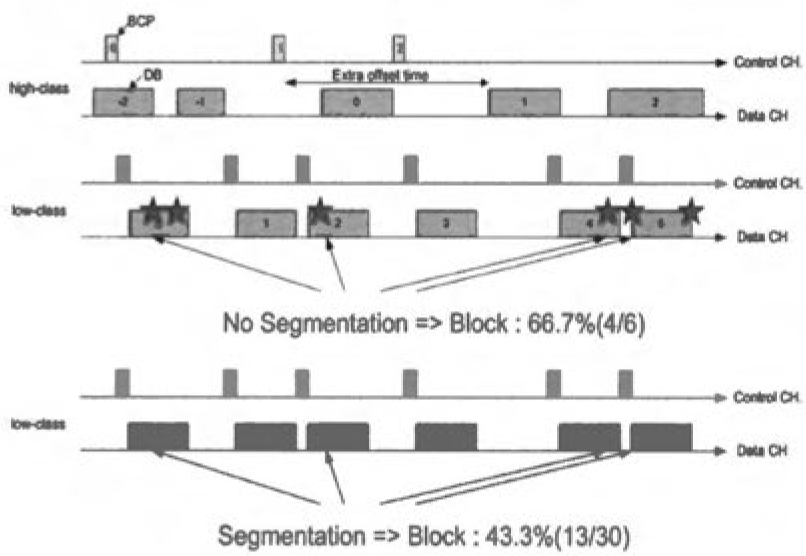


Figure 9 Burst Segmentation Scheme

3.2.2 Burst Synchronization: Slotted Burst Transmission

Burst synchronization scheme, which idea is borrowed from the slotted Aloha protocol, is also considered. By initiating bursts transmission synchronously, the overall blocking rate could be almost reduced by half theoretically.

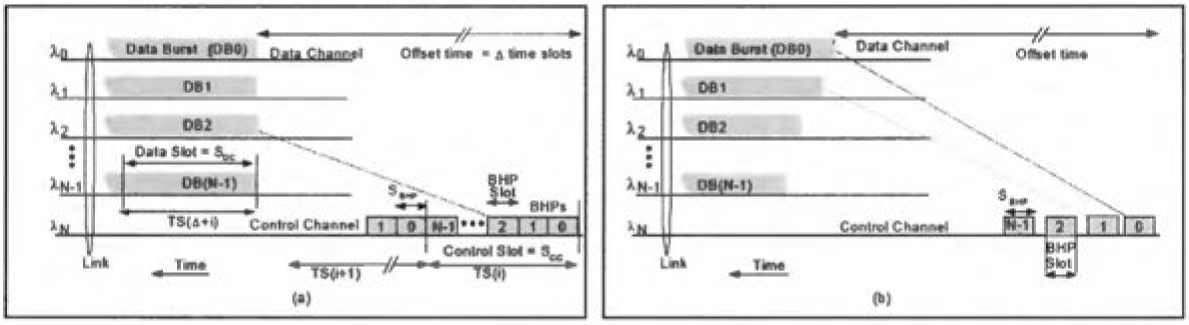


Figure 10 (a) The Synchronous Slotted and (b) The Asynchronous Unslotted Transmission [17]

3.2.3 Burst Contention Resolution

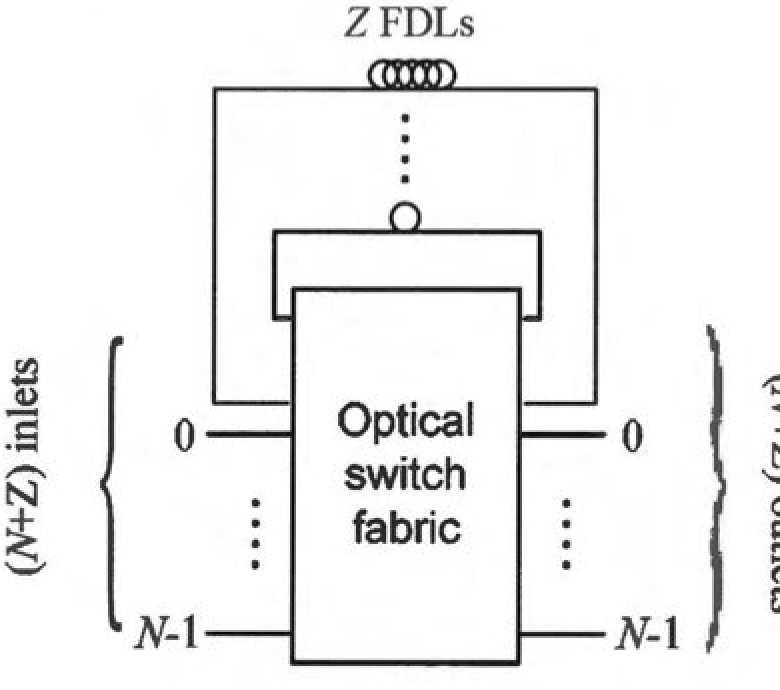


Figure 11 OBS Switch with Different FDL Arrangement [18]

By implementing optical buffers such as FDL and buffering burst, some bursts could avoid burst blocking. This scheme needs sophisticated time management as well as having long fibre line.

3.3 Research Hypothesis

3.3.1 Burst Assembly Hypothesis

A number of burst assembly algorithms have been discussed. The traditional or rather basic ones are time threshold based algorithms and burst length-based (size threshold based) algorithms. Another burst assembly algorithm which was proposed is the mixed or hybrid time / length algorithm. Other variations of these algorithms were also presented. Additionally, there have been quite a number of burst assembly algorithms which are based on traffic prediction/forecasting.

3.3.2 Time-based Burst Generation Hypothesis

With time-based algorithms, a timer is started at the start of each burst assembly cycle. When a determined fixed time is expired, all packets that would have arrived during that period would be assembled into a burst. In this scheme a minimum burst size is set. Therefore all bursts generated should be almost same. When choosing the value of time threshold as large values may lead to unnecessary packet delays at the edge. The other problem is that if the value is small, many small bursts will be generated and that would lead to high control overhead at the core nodes

3.3.3 Length-based Burst Generation Hypothesis

Burst length based algorithm also known as size threshold algorithm, unlike the time-base algorithm, this algorithm uses a fixed burst size to decide the generation of a burst. Once the size has been reached a burst is assembled and sent to the corresponding output port. The shortcoming of this scheme is that of depending on traffic, it may take long for size to be reached and result in undesirable delays at the edge node. When traffic is high, with a smaller value of size, many bursts will be produced resulting in high control overhead at the core nodes.

3.3.3 Time / Length Burst Hybrid Hypothesis

To deal with the problems aforementioned issues, a hybrid of the two schemes is considered. With the hybrid scheme a burst is assembled when time or size is reached to certain value, whichever comes first.

CHAPTER 4: RESEARCH AREA

4.1 Research Definition

To study the OBS performance improvement scheme and to analyse the performance of TCP layer.

1) Improving OBS blocking rate
2) Analysing TCP performance of the evolved optical burst scheduling scheme

4.2 Research Goals

1) Considering OBS scheme to overcome high burst loss rate
2) Performing mathematical analysis on:
    2.1) Blocking rate or packet loss rate;
    2.2) Packet delay;
    2.3) TCP round trip time.
3) Developing strategies of OBS in Optical communication
4) Analysing performance variation of TCP on OBS

4.3 Estimated Results

1) Throughput in TCP layer regarding:
    1.1) End to end packet delay
    1.2) Link utilization
2) End to end performance regarding:
    2.1) Burst loss on TCP
    2.2) Packet loss in burst

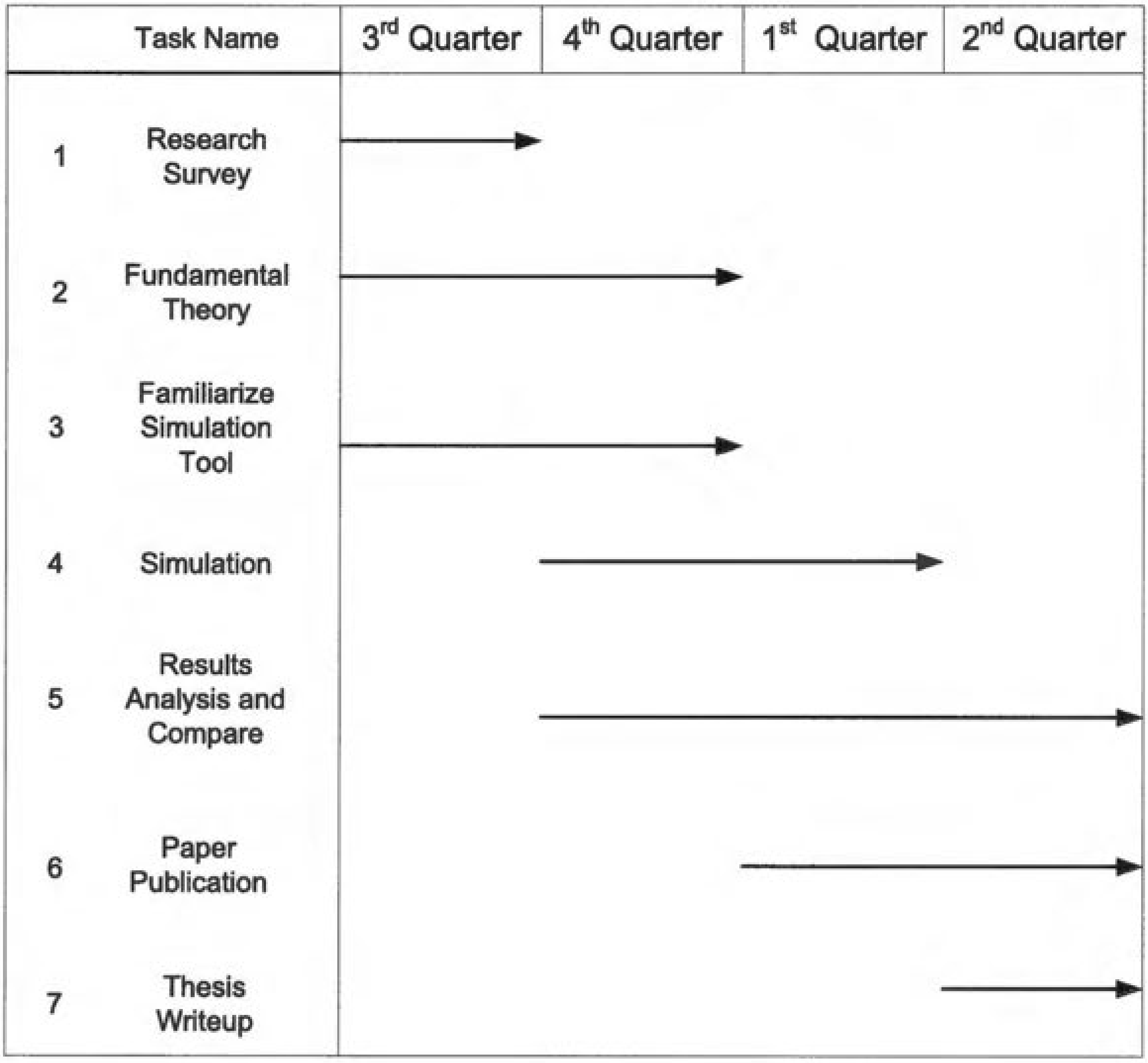
CHAPTER 5: METHDOLOGY AND TIMELINE

5.1 Methodology

The methodology of the research will be as follows:

1. Surveying previous works
   1.1. To improve OBS system based on current technology
   1.2. To proceed further researches
2. Designing evolved performance scheme (EPS)
3. Analysing and verifying proposed scheme by simulation:
   3.1. Use NS-3 as open source
   3.2. Change data transmission mechanism in NS-3 to implement OBS module
   3.3. Calculating the TCP throughput according to EPS
4. Comparing the simulation results to theoretical analysis
   4.1. Emulating theoretical model for EPS using Queuing Theory
   4.2. Estimating the throughput parameters

5.2 Timeline


Task Name
3rd Quarter
4th Quarter
1st Quarter
2nd Quarter
1 Research Survey
2 Fundamental Theory
3 Familiarize Simulation Tool
4 Simulation
5 Results Analysis and Compare
6 Paper Publication
7 Thesis Writeup

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